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A Preliminary Survey of the State of the Art in Simulation-Based Development and Certification to Support Digital Aircraft Design Research

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Abstract: Many safety critical domains require certification of a product before it can be released to the market. On the one hand, simulations and digital methods allow for cheaper and faster assurance of properties. On the other hand, the new and different methodology implies completely new requirements. We provide a general overview of the field and focus on naming, use cases, stakeholders, and quality criteria. We also highlight the needs of simulation users for research. We show that the naming in the different domains for virtual certification is widely spread, but the research needs aim into the same direction.

Keywords: Virtual Certification; Certification by Analysis; Simulation; Development; Certification; CbA; Numerical method; Simulation Based Development

1 Introduction

Certification is a critical step in the development of novel aircraft. The current certification process requires the iterative construction of physical prototypes of the aircraft, which then undergoes numerous tests to ensure its airworthiness. Each iteration is a waterfall process comprised of design, prototype construction and tests. Only after a successful test a certification can be obtained. If the test fails the whole iteration has to be redone which lengthens the time from initial design to final market-ready product.

A major research trend in aerospace engineering is the digital transformation of the aircraft development process, which includes the certification of the aircraft [Ma21; Ma22]. The authors are working at the Virtual Product House (VPH), an initiative of German Aerospace Center (DLR) which aims to develop novel methods and processes for virtual aircraft

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development. This includes the development of higher fidelity simulation methods, the development of composite simulations that simulate the aircraft manufacturing process, and the development of methods for long-term storage of simulated data. During this work we have observed that a number of requirements towards this newly developed methods are independent of the aviation domain, e. g., the requirement to record the provenance of simulation data, or the necessity to store these data over the life-time of the product. Similarly, some of the newly developed methods are also independent of the aviation domain. This includes, for example, the visualization of the execution of composite simulations [MSW23], or the integration of such composite simulations with a data management system [Dr22].

Based on this observation, we suspect that similar developments are currently taking place in other regulated domains where safety-critical products are certified before entering the market. These include, for example, the space industry, the automotive industry, and the medical industry. Our initial goal is to determine the current state of the art in digital transformation of the product development and certification process across multiple domains. This is complicated by the fact that the digital transformation of the engineering process is still a nascent field, with very few cross-domain standards developed to date.

Even within aviation, work related to digital transformation is sometimes discussed under the term "virtual development and certification" and sometimes under the term "certification by analysis." The latter term implicitly includes simulation-based aircraft development.

Our goal is to identify research groups, existing results, and nomenclature across domains. This will facilitate the reuse of results and methods. To this end, we plan several activities:

- First, we identify researchers working towards virtual certification and ask them to answer a few standardized questions regarding the state of the art of virtual certification in their respective domain.
- Second, we use the results of the first step to identify key contributors to the topic of virtual certification and conduct in-depth interviews with these contributors.
- Third, we use the results of the in-depth interviews to conduct a structured literature review to gain a broader understanding of current research trends in different domains.

In this work, we present preliminary results of the first stage of this research plan. In Section 2, we give an overview over the digital transformation of the aircraft development process as it is understood at VPH. There, we moreover identify open questions in virtual certification for aircraft, which we believe to be important in other domains as well. Afterwards, we describe our research plan for the questionnaire in greater depth in Section 3. Subsequently, we give an overview over preliminary results of the initial phase in Section 4. Finally, we discuss our next steps in Section 5.

2 Virtual Certification at VPH

The VPH [Ge] is a research collaboration comprised of research institutes as well as aviation industry partners, and members of the European Union Aviation Safety Agency (EASA).

It focuses on the enhancement of digital methods for aircraft development, testing, and certification. The long-term goal of VPH is to develop methods that allow for a completely virtual certification of aircraft and aircraft parts. The intended development and certification process is mapped to a digital tool-chain containing abilities from various aviation-related disciplines.

In VPH the whole process is seen as a digital end-to-end process, starting with requirements over virtual manufacturing to a virtually tested and certified product; Rädel et al. [Rä21] and Lange et al. [La21] give an in-depth description of this process. This process is realized using the workflow engine Remote Component Environment (RCE), which allows engineers to design and execute highly distributed tool-chains. For RCE, refer to Boden et al. [Bo21] for a technical description and Flink et al. [Fl22] for a user-focused introduction. The VPH tool-chain comprises several discipline-specific capabilities, such as virtual methods for testing an actuation system due to Hollmann et al. [Ho22], aerodynamic simulations due to Zakrzewski et al. [ZLH22], or automated aircraft model generation and sizing due to Führer et al. [Fü16].

The VPH follows the long term goal of virtual certification. Hence, a necessary subgoal is the credibility of our data and its processing within the VPH tool-chain. Thus we research how provenance data, i. e., information about the origin of data, has to be created and stored during and after the execution of the tool-chain [MSW23]. A data-driven view on this topic is given by Dressel et al. [DD21] and Dressel et al. [Dr22].

To be able to use simulation data for development and certification, engineers have to approve that their results map to a physical test, i. e., they have to ascertain the validity of the simulated result. Thus we aim to determine whether domains other than aviation use quality criteria or even a metric for validating their simulation results.

While working on the topic of data provenance at VPH, we observed that many data-related research questions are not specifically related to aviation. Therefore, these research questions related to data provenance are likely to either be addressed or to be of use in other domains. We already showed in previous work how provenance data is generated and stored in the current VPH tool-chain [DD21; Dr22]. Our current solution, however, has not yet been shown to scale to larger tool-chains. Furthermore we aim to investigate methods that allow data to be stored together with its provenance for the lifetime of the developed product. Since the lifetime of an individual product line in aviation often reaches several decades, this is decidedly non-trivial.

No model will ever exactly reflect the real-world situation. For certification, we need to quantify the difference between the model's prediction and the real-world phenomena. Thus, quantifying the uncertainty of model results and the models' robustness against minor deviations in the input data become an important topic. We are interested in how other domains deal with this matter.

3 Methodology

To gain initial insight into the processes used in domains that are supposed to use simulations for development and certification (not only limited to aviation), we created a questionnaire asking respondents to give an overview over the use of simulations for product development in their respective domain. As this is performed in the initial stage of our research we only asked high-level questions to gain a broad insight into this field. We show that questionnaire in Table 1. We sent out a questionnaire to ~30 experts from the domains automotive, aviation, space, biotechnology and maritime and received the answers of ten researchers in the automotive domain. Moreover, we answered the questionnaire ourselves to obtain comparable answers from the aviation domain. We show detailed information about the participants' demographics in Table 2.

Q1	What terms are used in your domain to address simulation-based development or certification? Mit welchen Begriffen wird in Ihrer Domäne die simulationsbasierte Entwicklung oder Zertifizierung adressiert?
Q2	How are simulations used in your domain for product development or product certification? You may name a representative process. Wie werden in Ihrer Domäne Simulationen zur Produktentwicklung oder -zertifizierung eingesetzt? Nennen Sie gern einen repräsentativen Prozess.
Q3	Where do you see the largest need for research and development in the area of simulation-supported development and certification? Wo sehen Sie den größten Forschungs- und Entwicklungsbedarf im Bereich der simulationsunterstützten Entwicklung und Zertifizierung?
Q4	By which institution (certification agency, standardization body, internal regulations, . . .) are those requirements defined whose satisfaction is indicated via the simulations? Durch welche Instanz (Zulassungsbehörde, Standardisierungsgremium, interne Vorgaben, . . .) werden die Requirements vorgegeben, deren Erfüllung die Simulationen anzeigen?
Q5	Which metrics / criteria of quality are used for simulation-based verification methods? Welche Gütekriterien / Qualitätsmetriken werden für simulationsunterstützte Nachweismethoden verwendet?
Q6	Which stakeholders are involved in simulation-based development or certification? Welche Stakeholder sind an der simulationsunterstützten Entwicklung oder Zertifizierung beteiligt?
Q7	Please state your current job title or your domain of work, respectively, as well as the duration of your experience in this job and associated training. Bitte nennen Sie Ihren aktuellen Beruf bzw. Ihre Branche sowie die Dauer Ihrer Berufs- und Ausbildungserfahrung in Ihrem Bereich.

Tab. 1: The questions posed in our initial E-Mail survey (original German formulation shown in small print).

Domain	Job Title	Experience
Aviation	Scientific Researcher	1 year
Automotive	Scientific Researcher	10 years
Automotive	Team of Scientific Researchers (9 Members)	3 to 20 years

Tab. 2: The demographics of the respondents to our initial survey.

In this initial step we aimed to keep the barrier to entry for the researchers as low as possible. Hence, we only posed a few brief questions. We moreover chose to conduct the survey via email instead of a more sophisticated survey tool, again to keep the barrier to entry as low as possible.

This questionnaire contained seven open questions, one of which only queried for demographic information. The other six questions are mapping to our research questions. Since all researchers identified spoke German fluently, we posed the questions in German.

We subsequently consolidated the answers from all participants and used them to evaluate our initial hypothesis and to inform our future research directions. We discuss these results in the following section.

4 Initial Results

We show the results of our preliminary and non-representative survey in Table 3. Where original answers were given in German, we have translated them into English.

We see that the answer to Q1 (Terms Used) directly supports our assumption that the digital transformation of the product development is discussed both in aviation as well as in the automotive domain. In fact, even though we only gathered data from two domains we obtained 19 different terms that are used in those domains to refer to simulation-based development or certification. Hence, we conclude that even within individual domains, no generally-agreed upon nomenclature has been established. Nevertheless we classified the answers to Q1 into the following non-distinct categories: a) In-the-Loop Testing b) Digital / Virtual Twin c) Simulations d) User-centric approaches e) Scenario-focused analyses f) Others

Moreover, we observe significant overlap between the individual terms given, both within and across the domains. In the automotive domain, e. g., both “User Study in Virtual Reality” and “User Study in the Driving Simulator” were named by researchers as types of user studies used in digital development processes. The common term “user study”, in contrast, refers to user studies without relevance to virtual development and is unfit as a characterizing term for the field. Similarly, the terms “Virtual Testing” and “Scenario-based Verification / Testing” were given by researchers from the aviation domain and the automotive domain, respectively.

Q1 (Terms Used)	User Study in Virtual Reality; User Study in the Driving Simulator; Safeguarding in the Digital Twin; Virtual Twin; Verification, Validation, Certification; Scenario-based Verification / Validation; Scenario-based Safety Assurance; Safeguarding / Testing / Engineering; xIL testing; Software-in-the-Loop (SiL) Testing; Hardware-in-the-Loop (HiL) Testing; Rare Event Simulation; Scenario-based Testing with the Aid of Driving Simulations; Traffic Planning and Optimization using Traffic Flow Simulations; Simulation-based virtual Integration Tests; Virtual Development; Virtual Certification; Virtual Testing; Certification by Analysis (CbA)
Q2 (Use Cases)	Feasibility Studies; Virtual Tests; User Studies; Recreation of equal Test Situations; Early error detection; Certification; Proof-of-concept in logistics; Virtual Integration Tests; Simulation of Surrounding Area; Demonstration of novel Interaction Concepts;
Q3 (Research Needs)	Validity of Simulations; Uncertainty Quantification; Robust Simulations
Q4 (Requirement Givers)	EASA; United Nations Economic Commission for Europe (UNECE); Regulation of the European Union; Users; Municipalities; Traffic Planners
Q5 (Quality Metrics)	Similarity to Validation Tests; Sharpness of the confidence estimate for the residual risk; Acceptance Criteria (ALARP, MEM,. . .); Criticality Metrics for Automated Driving
Q6 (Stakeholders)	OEMs; Tier 1 supplier; Approval authority; Vendors for Software Development Tools; Standardization Committees; Ministries (e. g. Transport Ministry); Urban Planners; Automotive Engineers; Research Institutes; Aircraft manufacturers

Tab. 3: Results from our initial survey

These observations show that we are unlikely to determine a fixed set of search terms or categories for a literature survey that allows us to obtain a comprehensive list of published works in this field across domains. Instead, we will most likely have to perform individual literature reviews per domain and consolidate the results to obtain a cross-domain review of the state of the art.

The answers to Q2 (Use Cases) show that the researchers expect various benefits from the digital transformation of the product development, ranging from earlier simplified demonstration of novel concepts, over error detection, to simplified certification. This is relatively unsurprising, as new developments are often met with major expectations of their usefulness once fully developed and deployed. These expectations often remain unmet during continued development [Ga].

Researchers' expectations contrast with their perceived requirement for future research, which we queried in Q3 (Research Needs). They identified the validity of simulations, uncertainty quantification, and the robustness of simulations as the most important future research fields for the digital transformation of product development. Researchers identified not only a gap between the results of simulations and the results of real-world tests when using current methods, but also different behavior of human test subjects when working with physical objects and when working with their simulated counterparts. Hence, we believe that future research in this field should not be limited to engineering disciplines with the aim to improve the fidelity of simulations, but that it should also include psychological research into the interaction of humans with simulations. We believe that this human-focused research is essential to retain the validity of product evaluations during the digital transformation.

Clearly, the digital transformation of the product development process involves the development, deployment and use of bespoke software. Typically, when developing software, developers are advised to focus on the requirements of the end-user to obtain an optimal software product [SC17]. The responses to Q4 (Requirement Givers) and Q6 (Stakeholders) show, however, that for the digital transformation of product development a bespoke design process may be required, as there exist numerous stakeholders and requirement providers that are not end users of the developed process. Moreover, the number of stakeholders already appears to be too large to involve all of them in an agile development process. In our opinion, this observation should inform future efforts towards digital transformation of product development. Research projects should consciously work towards involving a representative subset of stakeholders, which may not coincide with the direct users of the research results.

The answers to Q5 (Quality Metrics) show that there is a lack of a criteria to decide whether a simulation is sufficient. We see that researchers conduct physical tests to validate the simulation results. They also mention the "sharpness of the confidence estimate" as a quality indicator. The questionnaire participants also mention acceptance criteria. The acceptance criteria mentioned, however, have the aim of determining acceptable risk. In our case, this amounts to deciding whether the risk of a potentially inadequate simulation is acceptable. This does not include judgements about the quality of the simulation. The same applies to criticality metrics as they give information about the consequences of a wrong quality estimation.

5 Conclusion and Future Work

In this work we have presented a research plan for investigating the state of the art in the digital transformation of the product development and product certification process in the aviation domain and the automotive domain. We moreover have presented hypotheses based on the results of an initial survey across researchers from the aviation domain as well as the automotive domain. Finally, we have gathered and presented initial data via this preliminary survey that allows us to conduct an in-depth elicitation of the state of the art of virtual certification across multiple domains. The results of our survey support the hypotheses set out in our research assumptions that a) the same research goals are pursued in different domains, and that b) researchers in different domains use different nomenclature to refer to identical or very similar procedures and aims. In particular, we found that the automotive domain faces the same challenges with regards to the fidelity of simulations and their validation as the aviation domain. Moreover, researchers in the automotive domain already consider the challenge of different behavior of human test subjects in virtual and physical environments, which has not yet been considered at VPH. We moreover found that aviation researchers and automotive researchers identified virtually identical research needs: The topics of simulation validity, uncertainty quantification, and robustness of simulations with respect to minor disturbances in the input data appear to be of equal importance to researchers in both domains. Finally, we found that the surveyed researchers did not explicitly mention the need for trustworthiness of simulated data or its long-term storage. In previous work, in contrast, we found both topics to be highly relevant to certifying agencies in aviation and assume that they will be relevant in other regulated domains as well.

We believe that our results indicate that research towards simulation-based development and certification for digital aircraft design can immensely benefit from increased cooperation with other domains. One example of a topic where aviation research can benefit is the human behavior in simulated and physical environments. While this topic is already being researched in the automotive domain, it is not yet under investigation in aircraft development. We believe, however, that this topic will eventually become relevant as a building block for the digital end-to-end process developed at VPH (Section 2).

In future work, we aim to widen our research questions to other topics like software timing performance or human interaction to systematically investigate the state of the art in the digital transformation of product development and certification. In contrast to our initial survey, we aim to address additional safety-critical domains in which products are regulated and subject to certification. This includes, e. g., the space domain, the development of medical hardware, and the ship-building industry. For these domains, we will elicit the state of the art in virtual product development and certification via a) conducting in-depth interviews with selected researchers working in regulated domains and via b) performing a systematic literature review of existing work.

When conducting the in-depth interviews our aim is two-fold: First, we aim to determine the nomenclature commonly used in the respective domains when referring to virtual certification. As our initial survey shows, relevant topics are addressed under different names in different domains. By determining relevant nomenclature prior to the literature review, we can ensure that we include all relevant information in the review. Furthermore we can gain deeper insights regarding our research questions, e. g. the research needs, by interactively enquiring additional information. Secondly, we aim to identify the primary publication venues for the digital transformation of product development and certification in the respective domains via the interviews. Our experience from aviation shows that relevant literature is often published as gray literature, i. e., as technical reports [Ma21] or as memoranda issued by certification authorities [EA20]. Hence, determining relevant publication channels in the respective domains will again allow us to ensure to comprehensively determine the state of the art in these domains.

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