Continuous Experimentation and the Cyber-Physical Systems challenge. An overview in literature and the industrial perspective.

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Abstract

**Context:** New software development patterns are emerging aiming at accelerating the process of delivering value. One is Continuous Experimentation, which allows to systematically deploy and run instrumented software variants during development phase in order to collect data from the field of application. While currently this practice is used on a daily basis on web-based systems, technical difficulties challenge its adoption in fields where computational resources are constrained, e.g., cyber-physical systems and the automotive industry.

**Objective:** To provide an understanding of what is the state-of-the-art of the Continuous Experimentation practice in the context of cyber-physical systems, and what is the practitioners’ feedback about this practice.

**Method:** A systematic literature review has been conducted to investigate the link between the practice and the field of application. Additionally, an industrial multiple case study is reported.

**Results:** The study presents the current state-of-the-art regarding Continuous Experimentation in the field of cyber-physical systems. The current perspective of Continuous Experimentation in industry is also reported.

**Conclusions:** The field has not reached maturity yet. More conceptual analyses are found than solution proposals and the state-of-practice is yet to be

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achieved. However it is expected that in time an increasing number of solutions will be proposed and validated.

*Keywords:* Continuous Experimentation, Cyber-physical Systems, Software Engineering

1. Introduction

Technology progresses at an ever-increasing pace: new ideas, new techniques, and new products are constantly being developed, threatening the industrial players with slower work methodologies. Product owners are thus forced to deliver value as quickly as possible in order to keep their edge. The software industry is a prime example of this trend, especially in some of its sub-fields, such as web-based software systems.

Responding to this need for fast-paced value-centred software evolution, a number of practices have emerged with the goal of accelerating the processes around the development and deployment phases of software products’ life cycle. Among them are some increasingly known and adopted Extreme Programming’s Continuous Processes: Continuous Integration and Continuous Delivery/Deployment, which respectively advocate the integration of new code from developers’ working copies into the main code tree often, ideally as soon as possible; and delivery or deployment of code to the products and systems as soon as it is integrated, where the difference between delivery or deployment consists in the presence or not of an automated deployment process. On top of these processes can sometimes sit an additional one, developed and adopted mainly in the context of web-based software-intensive systems, called Continuous Experimentation. It promises to introduce a real-world data feedback stream that can guide the development and evolution of existing and new features.

1.1. Background

Continuous Experimentation is a practice that is based on the idea of multiple A/B testing and relies on the fast release channels offered by Continuous
Deployment. It results in having in a system or product the possibility to always run one or more different instrumented versions of the software in order to evaluate their performances, with the long-term goal of improving the system software via a series of incremental improvements validated from the field of use. In this sense, Continuous Experimentation differs from A/B testing in which it allows to run A, B, and possibly more versions of the software on the same platform, while it executes its normal tasks. A more detailed description of this practice can be found in Section 2.

Cyber-physical systems are integrations of computation and physical processes (Lee 2008), which means that these systems are immersed in the physical world and interact with it as the origin and/or result of their computation. This definition is quite broad and includes low-power and low-capabilities devices that are an important focus in some research and industrial areas, e.g., the Internet-of-Things. However, due to the computational and connectivity needs that a practice like Continuous Experimentation exhibits, the cyber-physical systems that are referred to in the context of this work are those systems that are built with or that could accommodate adequate processing power and at least occasional connectivity capabilities.

Vehicles, which nowadays can contain more than a hundred of cyber-physical systems (Hiller 2016), are considered by the authors as a sort of “systems of cyber-physical systems” capable of fulfilling the aforementioned needs. Additionally, many automotive companies are joining the trend of adding to and improving their software capabilities to provide as much automation as possible to their customers. This means that they have the capability and the interest in exploring possible practices that can help a desirable -for their customers-evolution of their software functionality. For these reasons, while the general interest is to enable Continuous Experimentation in cyber-physical systems, the scope of this article will focus on the automotive systems. This choice does not intend to exclude all other possible fields or systems, but before Continuous Experimentation could be applied in many of the current cyber-physical systems sub-fields there are still several technological challenges yet to overcome com-
pared to the ones that the automotive systems face at the present development stage.

1.2. Motivation and Research Goal

While the use of Continuous Experimentation is a reality on web-based software-intensive systems or smartphone apps, this is still far from true in the field of cyber-physical systems.

Research Goal: This paper aims at providing an overview of the engagement on the Continuous Experimentation practice in the context of cyber-physical systems.

The Research Goal was divided in the two following Research Questions and two different research methods were applied to answer them:

RQ1 : In the context of cyber-physical systems, what is the state-of-the-art of Continuous Experimentation?

RQ2 : In the context of cyber-physical systems and more specifically the automotive industry, what feedback do the practitioners provide about the Continuous Experimentation practice?

To achieve the Research Goal and answer RQ1, a systematic literature review has been conducted to shed light on the link between the research and this field of application. The resulting papers, which were included, are listed in Table 4 and summarized in Section 5.1. To answer RQ2, a series of case studies were conducted at automotive companies, collecting feedback from a number of industrial representatives. The results are described in Section 5.2.

1.3. Contributions

This article claims the following contributions:

C1 : drawing the state-of-the-art on the topic of Continuous Experimentation applied in the field of cyber-physical systems;
C2: identification of main challenges posed by Continuous Experimentation for automotive practitioners; and

C3: identification of main opportunities posed by Continuous Experimentation for automotive practitioners.

1.4. Scope

The scope of this work is the bond between the Continuous Experimentation practice and the cyber-physical systems field, as opposed to studying the Continuous Experimentation practice in any possible field of adoption. This applies generally for both the Research Questions, but even more specifically for RQ2, where the scope is further focused on the automotive field. This choice is reflected by the keywords chosen in the literature analysis, where articles were included if they would express the link between these topics.

1.5. Structure of the document

Section 2 explains more in details the Continuous Experimentation practice; Section 3 describes the research strategy adopted in this study; Section 4 lists and summarizes relevant related works; Section 5 reports the results of this work; Section 6 discusses the results and their possible implications; finally, Section 7 concludes this article, describing possible directions for future efforts.

2. Continuous Experimentation

Building upon the aforementioned Continuous methodologies, Continuous Experimentation is one Continuous practice that has recently gained momentum both in academia and among industrial practitioners in the field of web-based software-intensive systems. The goal of Continuous Experimentation is to enable the product owner to steer the development of new functionality by measuring their impact in terms of real-world data with respect to one or more chosen metrics. This is achieved by deploying instrumented variants of the
“official” software, the experiments, through a process inspired by scientific experimentation that on the organizational side involves several figures and is composed by the following steps (Fagerholm et al., 2017):

Step 1: the product owner has a development plan for the product, which is based on assumptions. One of these assumptions is chosen to be tested;

Step 2: the data scientist receives the assumption and draws an experimentation plan comprising the details of the experiment to be run, the type of data that is expected and the analysis that will be performed on them. At this step, a role knowledgeable about the system may be involved, complementing the data scientist’s plan with his expertise on the system’s capabilities;

Step 3: the developer receives the experimentation plan and implements it, while the release responsible roles deploy the experiment-primed software to the systems.

From a more technical point of view, instead, the Continuous Experimentation process can be divided into the following phases, as shown in Fig. 1:

Phase 1: the user (or system) base is defined, i.e., the set of users or deployed systems available for experimentation purposes;

Phase 2: the user base is divided in a number of significant partitions depending on the goal of the experiment, e.g., geographic localization, time of the day, etc. To each of these partitions, except for a “control partition”, an instrumented experiment is deployed. Each experiment is a different variant of the software with a new or different functionality to be tested;

Phase 3: the results from the experiments are collected and relayed back to the product owner and data scientist;

Phase 4: the collected data is analyzed, possibly using sound statistical methods
to remove noise and ignore human bias, and finally the best-performing experiment is identified;

Phase 5: according to a fitting set of goal- and experiment-dependent metrics, the experiment that performed best is chosen for global adoption across the user (or system) base.

Figure 1: Timeline of the phases of the Continuous Experimentation process

3. Research Method

To assess the Research Goal and its Questions, a multi-method approach was devised in order to engage with different strategies for the Research Questions and gain a wider perspective on the topic. To answer Research Question 1 the chosen approach was a systematic literature review, composed of both a query search and a snowballing phase (Kitchenham et al., 2015). For Research Question 2 a multiple case study was devised in order to collect feedback from
industrial practitioners (Runeson and Höst, 2009). An overview of the research strategy is shown in Fig. 2

3.1. Literature Review (RQ 1)

The first goal of this work is to illustrate the state-of-the-art for Continuous Experimentation in the field of cyber-physical systems. To do so, a literature review has been performed following the guidelines expressed by Kitchenham et al. (2015).

3.1.1. Search strategy

The search string was initially based on relevant related works that explored the literature with the aim of covering what progress has been made about the general study and adoption of Continuous Experimentation (Ros and Runeson, 2018; Auer and Felderer, 2018). As our goal is to focus on the adoption of Continuous Experimentation in cyber-physical systems, in the example of the automotive industry, we added to the search string relevant terms that would steer the scope of the search to our needs. Due to the novelty of the Continuous Experimentation practice and the lack of a globally accepted name in all the sub-disciplines that adopt this practice or variations thereof, many synonyms were needed in the search string in order to aim for inclusiveness. The majority of these search terms were used also by those related works that run comprehensive literature explorations. The variation problem does not appear for the cyber-physical systems field, which is a more established research context with a widely accepted terminology. The final string is thus:
The search string was queried on the following databases: ACM Digital Library, IEEE Xplore, Scopus, and Web of Science, returning a total of 192 publications (results up to date as of October 2019). To improve the completeness of the search results, as suggested by Kitchenham et al. (2015), a set of 12 papers were used as the basis for a manual backwards snowballing phase, which added 211 publications. The papers were chosen among the works included in past literature explorations (Ros and Runeson, 2018; Auer and Felderer, 2018; Mattos et al., 2018) based on how close their scope and focus was to this work.

Successively the duplicates removal phase took place. All results from the database and snowball search were collected in CSV format and a script comparing entries by publication title removed works which appeared more than once.
3.1.2. Selection criteria and process

The selection phase is performed after duplicates are removed, and is based on a set of selection criteria. The selection criteria determine whether a publication is part or not of the results set, shaping the conclusions one can draw from the study. As such they are a fundamental building block of the study and require to be carefully decided in order to include all and only those publications which are relevant to the topic. Two inclusion criteria were adopted and both had to be fulfilled by each study in order to be included. The criteria were:

- The study has a focus on Continuous Experimentation or A/B testing as a process, as opposed to a single test or experiment
• The study has a focus on the Continuous Experimentation process in the field of cyber-physical systems, i.e., considering the resource limitations that ensue as opposed to Continuous Experimentation performed on web systems.

A publication was instead excluded when any of the following exclusion criteria were met:

• The publication is not in English

• The publication is not peer-reviewed

• The publication is not a full paper (as opposed to a position paper, for example)

• The study is not a primary study

• The study does not focus on the Continuous Experimentation process or live testing of software

• The study does not include any considerations about the cyber-physical systems field

A summary of the number of results from the database search, backwards snowballing, duplicate removal and selection phases can be found in Table 1.

| Database Name       | Number of hits |
|---------------------|----------------|
| ACM Digital Library | 39             |
| IEEE Xplore         | 13             |
| Scopus              | 125            |
| Web of Science      | 15             |
| Total database hits | 192            |
| After snowballing   | 403            |
| Included publications | 8             |
To strengthen the confidence in the resulting included publications, a test-retest approach (Kitchenham et al., 2015) was employed, which means repeating (after a suitable time delay) some or all of the study selection actions in order to compare the outcomes.

3.2. Case Study (RQ 2)

In order to complement the systematic literature review and to additionally broaden the scope of the results, a multiple case study was devised to obtain empirical data from automotive industry representatives. This multiple case study extends the work reported by the authors in a previous article, where another multiple case study was performed adopting the same methodology, with the aim to extend, complement, and further validate the combined results (Giamo et al., 2019). In this study the novel multiple case study is referred to as “current multiple case study” while the previously reported one as “previous multiple case study”. The goal of the case studies was to ask the representatives the following working questions:

WQ1 : What are the advantages that the Continuous Experimentation practice would bring in the context of autonomous driving with respect to their professional role in industry?

WQ2 : What are the challenges that the Continuous Experimentation practice would face in the context of autonomous driving with respect to their professional role in industry?

3.2.1. Format of the case study

The case studies were conducted in a workshop format, each of them lasting between 1.5 and 2 hours, depending on the number of participants. During the workshops, one of the authors would lead it through its different phases, while the other authors would assist and take notes. The format was structured in four phases as follows:
Phase I: The workshop would begin with a presentation having the goal of establishing a common understanding and vocabulary of the Continuous practices, i.e. Continuous Integration, Continuous Delivery/Deployment, and Continuous Experimentation. This phase would last around 20 minutes;

Phase II: After the initial presentation, the participants were asked the two working questions about Continuous Experimentation, i.e. WQ1 and WQ2. This phase would last around 30 minutes, during which the participants would individually write their answers, each different idea on a different note;

Phase III: The participants were asked to go through their notes to explain and clarify the meaning and reasoning behind each of them. Each note would then be placed next to others expressing similar ideas on a whiteboard, thus creating clusters around common ideas. This phase would last around 40 minutes;

Phase IV: An infrastructure model for Continuous Experimentation devised for companies with web-based products (Fagerholm et al., 2017) was introduced to the participants. The aim was to start a discussion about the model and its criticalities if it had to be applied to the automotive industry. This phase would last around 15 minutes.

The format of these case studies was based on open questions focused on a structured topic, categorizing them as a series of semi-structured case studies (Runeson and Höst, 2009). This approach was chosen since it fits the exploratory and explanatory goal of the case study by promoting the participants to provide original feedback.

Two automotive companies were chosen to run the described case study. Company A is manufacturing heavy vehicles for various commercial operations. From this company 3 representatives joined the case study, 1 manager, 1 team leader and 1 engineer. Company B is producing consumer vehicles. From this company 15 employee took part in our study, where 1 of them was a manager,
7 team leaders and 7 engineers.

The overall variety of roles is considered a strengthening factor due to the increased diversity in points of view and resulting perspectives and discussions.

Due to the strong connection between the present multiple case study and the previously reported one (Giaimo et al. 2019), some details about the composition of the latter will follow. The previous series of case studies involved four companies, adding to the two aforementioned novel cases. They comprised two automotive OEMs (Original Equipment Manufacturers) in this article named Companies C and D, a Tier-1 supplier named Company E, and an autonomous driving electric vehicle start-up company named Company F. The participants roles were: from Company C, 3 software developers, 1 team leader and 1 manager; from Company D, 2 software developers and 2 team leaders; from Company E, 1 software developer and 2 team leaders; lastly, from Company F, 1 software developer and 1 team leader. To avoid biasing the participants of each one case study, the themes and discussions resulting from any other case study were not disclosed.

4. Related Work

Research and literature on Continuous Experimentation are growing in time, as an increasing number of universities and companies acknowledge and study its potential. Some of these studies are relevant and related to the goal of the present work and their respective differences with this study will be outlined.

Fagerholm et al. (2017) defined their “RIGHT” model for Continuous Experimentation, an organizational model defining the tasks and artifacts that the different roles involved in the planning and implementation of a software product should manage in order to enable a smooth experimentation process. Their work however does not focus on the specific issues that cyber-physical systems face, e.g., the resource constraints that may challenge the planned experiments or the impact that the presence of hardware components may have on the release of experiments.
Ros and Runeson (2018) run a literature review to investigate what companies and what experiments are mostly performed in Continuous Experimentation. They mention attempting a pilot study in 2016, which did not find enough publications on the topic; independently from them, we also attempted a pilot study in that year, finding not enough published works as well. Their findings draw a picture, in which mainly big companies perform the most experiments, which are more often aiming at visual changes than algorithmic changes, the latter case being performed only with A/B experiments. They also investigate which Continuous Experimentation research sub-topics are explored in literature, finding that experimentation infrastructure, challenges and statistical methods are the three most common ones. They mention but not focus primarily on the connection between Continuous Experimentation and cyber-physical systems.

Auer and Felderer (2018) also run a literature review aiming at assessing the state of research on Continuous Experimentation and its main topics, contributors, and research types. They draw a picture of how Continuous Experimentation is spreading as a research subject to multiple venues and academic parties and similarly to Ros and Runeson (2018) finds a high presence of studies on statistical methods, infrastructure, and organizational topics applied to Continuous Experimentation. As well as the previous publication, they mention but do not focus on the connection between experimentation and cyber-physical systems.

Mattos et al. (2018) run a literature review to identify challenges to the Continuous Experimentation process in cyber-physical systems that were the object of a case study where they tried to identify possible solutions. While their work considers Continuous Experimentation and cyber-physical systems, in their literature review the search query is generally on Continuous Experimentation and thus does not express the strong link with embedded systems that we are trying to highlight in the present work.
5. Results

5.1. Literature Review

The studies included in the literature review are summarized in the following tabs; additionally, they can be found listed in Table 4.

| Title: Challenges and Strategies for Undertaking Continuous Experimentation to Embedded Systems: Industry and Research Perspectives (Mattos et al., 2018) |
|---|
| Scope: Continuous experimentation and the challenges and requirements that embedded systems companies have to run experiments in their systems. |
| Research Goal: Exploring the challenges posed by the adoption of continuous experimentation in embedded systems. |
| Methodology: Literature review and multiple case study based on interviews and workshop sessions. |
| Contributions: Challenges from literature and possible strategies to overcome them. |
| Conclusions: The set of identified challenges are presented with a set of strategies and solutions to overcome them. |
| Threats to Validity: Scope of the literature exploration, generalization of the collected challenges. |
Title: Considerations About Continuous Experimentation for Resource-Constrained Platforms in Self-driving Vehicles (Giaimo et al., 2017)

Scope: Continuous Experimentation and its technical challenges on cyber-physical systems on the example of automotive systems.

Research Goal: To assess the scarcity of resources that could disrupt or prevent the adoption of Continuous Experimentation on cyber-physical systems.

Methodology: Exploratory study, design science.

Contributions: Three technical strategies to circumvent the physical limitations of cyber-physical systems with the aim of enabling Continuous Experimentation; description of software architecture capabilities that would enable them.

Conclusions: The execution strategies are presented together with their prerequisites in the software infrastructure.

Threats to Validity: Validation underway but not reported.

Title: Design Criteria to Architect Continuous Experimentation for Self-Driving Vehicles (Giaimo and Berger, 2017)

Scope: Architectural needs for Continuous Experimentation on self-driving vehicles.

Research Goal: The goal of the paper is to find properties of the software architecture and process required to enable Continuous Experimentation for a complex cyber-physical system.

Methodology: Literature analysis and design science.

Contributions: List of properties or features that a software architecture should provide in order to enable Continuous Experimentation on cyber-physical systems.

Conclusions: The study concludes underlining that cyber-physical systems can benefit from Continuous Experimentation, although technical challenges still exist that impede a widespread adoption.

Threats to Validity: Scope of literature exploration.
Title: From Opinions to Data-Driven Software R&D (Olsson and Bosch, 2014)

Scope: Embedded software companies.

Research Goal: The goal of this paper is to find mechanisms that help companies confirm that the product features they prioritize are of value for customers.

Methodology: Multiple case study.

Contributions: A process model to guide the companies to adopt practices that return a feedback from their customers.

Conclusions: The model enhances productivity due to its focus on customer validation of the companies’ efforts.

Threats to Validity: Construct validity, external validity.

Title: Post-deployment Data Collection in Software-Intensive Embedded Products (Olsson and Bosch, 2013)

Scope: Companies involved in large-scale development of embedded products.

Research Goal: To provide an overview of post-deployment data usage in the embedded products’ industry.

Methodology: Multiple case study.

Contributions: This work presents an inventory of techniques used for customer involvement and customer feedback collection before, during and after product development. It also presents opportunities for more effective product development and evolution by collecting customer data in the post-deployment phase of software development.

Conclusions: The authors highlight limitations in the research and practice of post-deployment data collection aimed at the improvement and innovation of the existing deployed systems, as opposed to troubleshooting.

Threats to Validity: One reported issue is that different individuals may have interpreted the same data in different ways.
Title: Architecture for Large-Scale Innovation Experiment Systems (Eklund and Bosch, 2012)

Scope: Embedded systems domain.

Research Goal: The goal of the paper is to define principles for the architecture of large-scale experiments.

Methodology: Design science, case study.

Contributions: Theoretic infrastructure for experiments on embedded systems.

Conclusions: The authors aim to fulfill the research goal by proposing an architecture for experiments called “innovation experiment system” while at the same time studying an industrial case of A/B testing on an automotive infotainment system.

Threats to Validity: Proposed architecture may not be complete, validation on only one case study presented.

Title: Eternal Embedded Software: Towards Innovation Experiment Systems (Bosch and Eklund, 2012)

Scope: Long-lived embedded systems.

Research Goal: To introduce the notion of “innovation experiment system” and to apply it to the context of long-lived embedded systems.

Methodology: Exploratory study, case study.

Contributions: The contribution of the paper is a discussion of the concept of innovation experiment systems, exploring the architectural implications of such systems, and illustrates a case study concerning an infotainment system in the automotive industry.

Conclusions: The proposed architecture for experimentation can help embedded systems to evolve and respond to changing context and requirements. However there are sub-domains of the embedded systems field where experiments may not be viable, effective or needed.

Threats to Validity: Validation on only one case study presented.
**Title:** Building Products as Innovation Experiment Systems (Bosch, 2012)

**Scope:** This paper looks at the evolution of the development process of Software-as-a-Service (SaaS) solutions and software-intensive embedded systems.

**Research Goal:** Address the application of experimentation, ranging from optimization of existing feature to the development of new features and products.

**Methodology:** Case study.

**Contributions:** A systematization of the proposed “innovation experiment system” approach to software development for connected systems, and the illustration of the model using an industrial case study.

**Conclusions:** The authors note that the traditional development approaches are being replaced by new ones, focusing on factors like continuous evolution and utilization of user data. The work proposes a development approach based on “innovation experiment systems” to constantly develop and test new hypotheses on the software.

**Threats to Validity:** Proposed systematization may not be complete, validation on only one case study presented.

5.2. Multiple case study

In this section the resulting data from the multiple case studies are collected. The notes written by the participants were analysed and grouped in semantic clusters, resulting in the two two-level lists that follow, one for the reported Advantages and one for the Challenges. In both description lists, each high-level theme (in boldface characters) contains one or more detailed items (in italic characters). Due to the complex nature of the problem, some items may be related to each other due to fundamental topics and issues that span and affect multiple thematic aspects. The connection between which item was mentioned in which companies, including the data from both the current and previous multiple case study, is shown in Tables 2 and 3.
| Category          | Advantage                        | Companies in current case study | Companies in previous case study |
|-------------------|----------------------------------|---------------------------------|---------------------------------|
| Safety            | Monitoring                       | B                               | D, E, F                         |
|                   | Reliability                      | B                               |                                 |
|                   | Active/passive safety opportunities | B                               |                                 |
|                   | Traffic prediction               | B                               |                                 |
| Speed             | Faster data collection           | A                               | C                               |
|                   | Faster functionality feedback    | B                               |                                 |
|                   | Faster time-to-market            | A, B                            | C, D, E, F                      |
| Quality           | Customer satisfaction            | B                               | D, E, F                         |
|                   | Improved quality                 | B                               |                                 |
|                   | Better world understanding       | A                               |                                 |
| Opportunities     | Reducing long-term costs         | B                               |                                 |
|                   | Monetization of data             | B                               |                                 |
|                   | Testing of 'bold' ideas          | A                               |                                 |
|                   | Improving future solutions' design | A                               |                                 |
|                   | Mechanical integrity             |                                  | E, F                            |
|                   | Easier testing                   |                                  | C, D, E                         |
|                   | Energy efficiency                |                                  | F                               |
|                   | Real-world data usage            |                                  | C, D, E                         |
|                   | Incremental delivery             |                                  | E                               |
|                   | Fleet view                       |                                  | C                               |

Table 2: Perceived Advantages in the Continuous Experimentation practice and the companies raising each point. The first column contains the category of each Advantage, which is named in the second column, the third contains the companies that mentioned the item during the current multiple case study, and the fourth contains the companies that mentioned the item during the previous multiple case study, if any.
| Category          | Challenge                                      | Companies in current case study | Companies in previous case study |
|-------------------|------------------------------------------------|---------------------------------|---------------------------------|
| Safety            | Impact measurements                            | B                               | D, E, F                         |
|                   | Responsibility                                 | B                               |                                 |
| Security          | Data protection and privacy                    | A, B                            | C, D, E, F                      |
|                   | Misuse of data                                 | B                               |                                 |
| Quality assurance | Complexity of software and operations          | B                               |                                 |
|                   | Data quality                                   | B                               |                                 |
|                   | Validation and verification                    | A                               | C, D, E, F                      |
| Costs             | Costs for experiment data management           | A, B                            | C                               |
|                   | Regulation changes                             | B                               |                                 |
|                   | Costs of experiments                           | A                               |                                 |
|                   | Tools to enable/support experimentation        | A, B                            | C                               |
| DevOps            | Data and configuration management              | A, B                            | C, D                            |
|                   | Software and hardware infrastructure           | B                               |                                 |
|                   | Global engineering                             | B                               |                                 |
| Hardware          | Resource constraints                           | A                               | C, D, E                         |
| -                 | Fallback Plan                                  |                                 | F                               |
| -                 | Regulations                                    |                                 | C, D, E, F                      |
| -                 | Versioning                                     |                                 | C, E                            |
| -                 | Performance                                    |                                 | E, F                            |
| -                 | Remote execution                               |                                 | E                               |
| -                 | Testing                                        |                                 | C                               |
| -                 | Heterogeneity                                  |                                 | D, E                            |

Table 3: Perceived Challenges in the Continuous Experimentation practice and the companies raising each point.
5.2.1. Advantages description list

Safety: Software-enabled auxiliaries to basic functions like braking and steering could reduce the risk of dangerous situations occurring during the products operational life. With a constant loop of experimentation and updates, the robustness of the software in unforeseen or perilous events would increase over time and therefore improve the overall safety of the system.

- Monitoring. With the possibility of sending and receiving data to/from the product, it would also be possible to find out about product issues in a faster way. The monitoring could not only be employed on the software aspects of products but also on the mechanical integrity of the vehicles, allowing product owners to be aware of and mitigate the impact of the wear and tear in their products.

- Reliability. Constant monitoring could result in a better localization of errors and miscalculations, leading to more robust and reliable products overall.

- Active/passive safety possibilities. Continuous experimentation would allow new possibilities for active and passive safety functionality, taking advantage of fast time-to-market cycles. Novel possibilities and techniques can be experimented and improved on the run.

- Traffic prediction. With the constant transfer of sensor data to the headquarters, engineers can develop functionalities that are based on an always-improving representation of the world. Such amounts of data allow for better prediction of traffic behavior, which in turn improves safety on the road.

Speed: It has been reported that one crucial benefit in achieving Continuous Experimentation is the resulting increase in the speed of software development, testing, and release processes.

- Faster data collection. With a constant connection between the headquarters and the vehicle, interesting data could be collected on demand,
allowing for fast and ad hoc analysis of system behavior. Instead of collecting data from controlled tests on test tracks, the OEMs would benefit from the real-world system usage thanks to the Over-The-Air (OTA) connection.

- **Faster functionality feedback.** Faster data collection also allows for faster feedback from the users about the products’ functionality. Preferences in terms of often-used or seldom-used functions can be detected and used to help the development process.

- **Faster time-to-market.** Updates would equally be fast-paced given that two-way OTA connectivity is established. Software could be updated regularly and without manual delivery of new versions. It could be faster to fix issues and improve the software establishing a more dynamic life-cycle. Instead of prototyping and running typical acceptance testing with a reduced number of users, the acceptance could be measured from real-world scenarios as fast as the data can be transmitted from the products back to the headquarters. Furthermore, simulations of the world can be enhanced thanks to the increasing amounts of data collected in the real world.

**Quality:** Quality has shown to be a concern of great importance in the adoption of Continuous Experimentation. The changes in the software process must not negatively affect the already conquered quality of the software and the customers’ satisfaction.

- **Customer satisfaction.** The functionality of the software is reassessed using data from regular usage of the systems. The customers’ preferences would be captured and implemented into the system through updates, improving customer satisfaction.

- **Improved quality.** Through constant feedback, the overall quality of the products would also be improved. Further, feedback on the performance of specific functions can be collected and assessed quickly.
• **Better understanding of the world.** Since experiments can be done at a larger scale than what is currently possible, the amounts of data would also increase. The systematic analysis of this large amount of data *upstreaming* from the products would result in a better representation of the world to the benefit of simulations and future development efforts.

**Opportunities:** Some opportunities were pointed by the practitioners in the case of adoption of Continuous Experimentation.

• **Reduced costs in the long run.** Incremental and constant delivery of functionalities may decrease the cost of development in the long run.

• **Monetization of data.** Data collected from the field can be monetized according to the owner company’s business goals.

• **Possibility to test bold ideas.** Companies would have the opportunity to test bold ideas in real-world usage scenarios. This is interesting since the life-cycle of systems in the automotive domains is considerably long (usually several years, if not decades).

• **Improving future solutions’ design.** Better design and development of new solutions in the future can be achieved thanks to better understanding of the real-world in combination with detailed understanding of how the products are actually used.

5.2.2. **Challenges description list**

**Safety:** Perhaps the biggest concern is how to ensure the safety of experimental versions of the system. Changes in the code base might negatively impact critical safety features. A robust strategy for obtaining a full understanding of such impacts is needed in order to deploy safe software to the vehicles. Safety requirements must also be guaranteed in the case of redundancy of hardware and software.

• **Impact measurements.** Safety-critical applications strive for consistency and means to measure the impact of changes to the code base. Such
measurements must occur before the deployment phase, which means that the real impact of changes would not be entirely under control. This scenario poses a challenge to testing, for instance, experiments that affect the control of the vehicle.

- **Responsibility.** In case of accidents involving systems running experiments, the responsibility may be up for discussion. In addition to the governmental regulations, there might be margins for interpretation upon eventualities.

**Security:** Another major concern discussed in the workshops was the aspect of information security. Safely storing and transmitting user data or software requires the implementation of robust security mechanisms.

- **Data protection and privacy.** Since both user information and experimental algorithms will move to and from the vehicle, one important concern would be the security of such communication. The integrity of the transmission must be preserved through security mechanisms that reduce the risk of interception, impersonation, or tampering by third-party entities. Furthermore, corporate secrecy might also play a role, since experiments will be embedded in products.

- **Misuse of data.** Personal customer data could be misinterpreted or used for improper purposes by the companies themselves.

**Quality assurance:** Continuous Experimentation is expected to bring an increase to software quality due to the inherent behavior learning. However, a number of topics were raised that could challenge the rise in quality, as follows.

- **Complexity of software and operations.** Running various instances of the software systems increase the complexity of the system. Multiple instances of the same software, including experimentation portions, also increase the complexity of the operations. Handling such increase in complexity poses an important challenge to Continuous Experimentation practitioners.
• **Data quality.** When data arrives at the development site, collected from the field, how much can it actually be trusted to be representative of reality? It could be the case that for determined purposes the data are not consistent enough to draw significant conclusions.

• **Validation and verification.** Also connected with the measurement of impacts, companies implementing Continuous Experimentation must develop and assess robust procedures that allow for proper validation and verification of the systems.

**Costs:** Industrial practitioners are concerned with the costs involved in implementing Continuous Experimentation. In particular, a novel hardware infrastructure would be necessary to accommodate software instances and transmit data to/from the target systems.

• **Data management.** Managing large amounts of data demands costs that must be accounted for when implementing Continuous Experimentation. For instance, the costs for storage, analysis, and transmission of the data collected by the systems in the fleet.

• **Regulation changes.** Regulatory changes might be unforeseen and demand fundamental changes in the business model. The impact on research and development is typically high with respect to costs and the implementation of new processes.

• **Costs of experiments.** There might be additional costs tied to the design and implementation of experiments in the Continuous Experimentation fashion.

• **Tools to enable/support experimentation.** There would be inherent costs to implementing and/or buying hardware, software, and analytical tools to enable or support Continuous Experimentation in a large-scale organization.
DevOps: Practitioners mentioned challenges related to DevOps processes when possibly implementing Continuous Experimentation.

- **Data and configuration management.** Collecting, structuring, and analyzing data obtained from the field would become an integral part of the development process. The large amount of data collected would pose a managerial challenge in Continuous Experimentation. To reduce the load for the systems in the fleet, practitioners may need to decide what data would be relevant for collection and analysis and what instead could be ignored.

- **Software and hardware infrastructure.** In the context of experimental applications, the process would require both a software and hardware infrastructure to realize Continuous Experimentation. From the necessary software stack to run applications on the vehicle, to the required hardware for executing extra portions of code.

- **Global engineering.** Several automotive projects contemplate global products, having an additional layer of complexity on the data collection. As an example, what could be a preference for a certain geographic market could be less desirable or possible to achieve in another.

Hardware: Additional hardware would most likely be needed to accommodate Continuous Experimentation in the existing systems. In some domains, such as the automotive field, adding weight and requiring extra space in the vehicle for additional equipment might be a crucial constraint.

- **Resource constraints.** A highly resource-constrained computational environment would limit the options for experimentation.

5.2.3. Complementing our previous study

The reported results extend and complement aspects that emerged in a previous multiple case study performed by the authors (Giaino et al., 2019). In
that study the same categories (in boldface characters) emerged for both Advantages and Challenges, with the exception of the “Sustainability” item in the Advantages section. A number of additional subcategories (in italic characters), however, were not mentioned in the discussions during the latest case studies and, hence, did not appear in the above description lists. These items in the Advantages list were:

**Safety**

- *Mechanical integrity.* Constant monitoring result in a slower wear and tear of mechanical components by interpreting situational/behavioral states of the system. Once identified, wear-prone situations could be avoided.

- *Easier testing.* Field testing on the fly makes it easier to detect bugs, and with the constant feedback it would be easier to find relevant test cases for the system.

**Sustainability**

- *Energy efficiency.* Unused functionalities can be disabled to reduce energy consumption. The data resulting from a constant monitoring of the hardware’s energy consumption can also be used to improve energy efficiency.

**Opportunities**

- *Real-world data usage.* Learning from data enables research and improvements of both the process and the product. Further, the collected data can be analyzed and/or sold as services.

- *Incremental delivery.* Large and complex functions can be delivered step-by-step. Certain functions can be implemented and updated at a later time.

- *Fleet view.* Companies may have the opportunity to obtain a comprehensive view of the behavior of their products based on the collected data from the fleet.
Finally, the non-repeated items in the Challenges list were:

**Safety**

- *Fallback plan*. In case of failure, a fallback plan must always be ready. With multiple versions of the software deployed, this solution demands a robust versioning system that allows safe rollback in case of emergencies.

- *Regulations*. Complying with strict governmental regulations (e.g., in the automotive domain) can be a challenge.

**DevOps**

- *Versioning*. Developers must acknowledge/monitor versions that are deployed. Different configurations of the same software may be deployed and running on different vehicles.

**Quality assurance**

- *Performance*. Running various instances of the software can be very demanding to the automotive hardware, which is typically resource-constrained.

- *Remote execution*. The risk of unwanted or unknown behavior of the system is increased. Moreover, updates could be at risk of not occurring due to poor, faulty, or non-existing network connections.

- *Testing*. Since most of the testing in the automotive industry is done manually, this stage represents very high costs. Further, developers may question “what is enough testing?”.

**Hardware**

- *Heterogeneity*. Systems with different hardware specifications pose a challenge in ensuring that new software versions are supported by the available hardware platforms with their different setups.
6. Discussion

6.1. State-of-the-art of Continuous Experimentation in the cyber-physical systems context

At this point in time the Continuous Experimentation practice has been recently studied in literature as noted also in (Auer and Felderer, 2018), although in the context of cyber-physical systems this has happened with a quite limited number of strategies and studies. As shown in the presented systematic literature review, the majority of studies have a high-level approach. This means that they try to tackle from a more conceptual point of view the difficulty of applying this practice to a new field which faces different challenges than the field from which Continuous Experimentation originates. Many of these studies are observational, in which a case study is run to analyze whether a certain hypothesis is met in practice (Mattos et al., 2018; Olsson and Bosch, 2014, 2013; Eklund and Bosch, 2012; Bosch and Eklund, 2012; Bosch, 2012). A minority of articles are instead design studies trying to draft possible solutions to the technical hurdles opposing the adoption of Continuous Experimentation on cyber-physical systems (Giaimo and Berger, 2017; Giaimo et al., 2017; Eklund and Bosch, 2012). This unbalance towards more theoretical studies is assumed by the authors to be a direct effect of the relative novelty of the practice in object in the field of cyber-physical systems: in time the authors expect to see an increase in more technical studies facing and overcoming the challenges identified in this more investigative initial period.

Drawing a comparison between these results and the ones reported in related studies, both Ros and Runeson (2018) and Auer and Felderer (2018) report that in Continuous Experimentation the studies on solution proposal or validation studies are the minority, while most studies are on statistical analysis and architecture, thus agreeing with what was witnessed in this systematic literature study. Moreover, from Ros and Runeson (2018) it emerges that experiments of any type in the embedded software context are a strict minority. An interesting note, although not directly connected to the current line of reasoning, is that
the same study reports that among the experiments they surveyed the almost
totality had as objective visual changes, as opposed to algorithmic changes or
the test of new features. An explanation could again be found in the novelty of
the field, where experiments, when actually conducted, are done so by starting
from the simpler steps.

6.2. Automotive practitioners’ feedback on Continuous Experimentation in the
cyber-physical systems context

Both companies in the current multiple case study highlighted that the most
clear advantage of adopting Continuous Experimentation would be a reduction
of the development time for new software. Many other desirable capabilities and
effects were brought up but interestingly not by representatives in both com-
panies. Some of the reported ideas had been stated also by other companies’
participants in the previous multiple case study, e.g., the possibility to monitor
the vehicle in terms of maintenance needs, the quicker data collection possibili-
ties, and the quality feedback given to the software by the users. New items also
emerged, notably such as the possibility to predict traffic patterns over time,
the monetization of the collected data, or even the possibility to test bolder
ideas than with the current tools and processes – although the practicality of
this last point is quite dependent on the context of the ideas themselves, since
safety consideration must be taken into account before developing experiments.

Drawing a comparison with the results of the previous multiple case study,
it is interesting to notice the relatively small overlap between the items in the
Advantages list collected in the current case studies and the ones collected during
the previously reported case studies, meaning that the remaining items and
considerations were not repeated. This could either hint at the broad spectrum
of possible applications that the Continuous Experimentation practice could
enable in this field, or at the uncertainty of the practitioners about what would
actually be possible and what would not, or possibly a combination of these
two elements. Considering the relative novelty of the practice in this context,
however, a certain degree of spread in the collected ideas is not surprising.
Moving the focus on to the Challenges items, it is possible to observe that, similarly to what happened with the Advantages, there are some items which were repeated and others that were unique for each single case study. Notably, the companies of the current case study agree that important challenges are, among the others, ensuring customers’ data protection and the management of the experimental data, together with the associated costs. Less unanimous but fruitful nonetheless were the discussions about interesting items such as the challenge of elaborating meaningful experiments, the problem of assigning responsibility in case of accidents, the trustworthiness of the collected data, or even the challenge of managing experiments running on systems distributed on a wide geographic scale, where cultural differences may have a bigger impact on the results than expected.

Comparing the previous multiple case study with the current one, some items did not emerge in the latest cases, e.g., the presence of a fallback plan in case of failures during the experimentation process, or the risks associated with needing to exchange data with a product in an area where it cannot establish a successful connection, or the challenge to manage heterogeneous hardware configuration in different product families. The overlap between the Challenges items in the two multiple case studies shows to be higher than what was seen in the Advantages list, meaning perhaps that more agreement is found when discussing obstacles to the adoption of Continuous Experimentation in this field.

6.3. Overview of Continuous Experimentation on cyber-physical systems, with a focus on the automotive field

The aim of this work is to provide an overview of the engagement in Continuous Experimentation in the context of cyber-physical systems, in the example of the automotive field.

From the literature study it emerged that most articles face the issues of enabling Continuous Experimentation on cyber-physical systems from a conceptual standpoint, focusing on case studies where some companies move tentative steps towards the adoption of experimentation as a means to improvement for
processes and products. Fewer studies try instead to propose solutions to more technical issues. These differences hint at a field which is still in its infancy, and where important issues are still unsolved and hurdling prospective scholars and practitioners.

These considerations are validated by the findings from the conducted empirical studies. In fact, this different approach resulted in a series of broad expectations and even broader issues that are currently preventing the adoption of experimentation in the industrial context, at least for what concerns automotive cyber-physical systems. This means that a state-of-practice has not yet been established, and it likely will not until at least a number of challenges will be solved or avoided, allowing this more constrained field to reap the same benefits that the Continuous Experimentation practice has brought to the web-based software-intensive systems applications.

6.4. Threats to Validity

A first threat to the validity of this study is the possibility during the literature exploration to have not found all the articles that are relevant to our topic. To reduce this chance a multi-method approach to the investigation was employed, complementing the query-based search with the snowballing phase.

Moreover, threats to the validity of the literature exploration results may lie in the selection process. A test-retest approach was employed to increase the trustworthiness of the selection outcome.

A threat to the validity of the multiple case study results is the possibility that the first phase of the case studies, which included a presentation, had biased the participants’ answers to the workshop questions. To limit the impact of this threat, the authors tried as much as possible to avoid content and examples that could influence in a certain direction the participants’ thinking but to establish a common vocabulary for the workshop.

Another threat to the validity of the conclusions is the absence of data triangulation, which involves running more than one time the same workshops in the same format to confirm the findings. The data triangulation was made
impossible by the limited availability of the industrial representatives that joined the case studies.

An additional threat is the low number of companies and participants from Company A. The limited number of people and companies involved means that the results may not be generalizable to other automotive companies or industrial contexts. However, the current multiple case study extends and complements a previous work published by the authors, where a multiple case study was structured and run with the same methodology with representatives coming from different companies, widening the scope of the combined results and strengthening their validity.

Finally, a possible threat to the validity of the results of this work is the difference in scope between the automotive field and the other sub-fields of cyber-physical systems. It may be possible that different types of cyber-physical systems may be more ready than vehicles to adopt Continuous Experimentation, but at the best of the authors’ knowledge this is not the case. Additionally, if this was indeed true, it would be expected that the results of the literature review would have hinted at this possibility.

7. Conclusions and Future Work

7.1. Conclusions

This work aimed at formulating an overview of the engagement on the Continuous Experimentation practice in the context of cyber-physical systems, uniting an analysis of the state-of-the-art achieved through a systematic literature review, to a multiple case study conducted with automotive industrial representatives. The resulting image is a field that has not reached maturity yet. High-level analysis studies are present in higher numbers than solution proposals and the state-of-practice is yet to be achieved due to the numerous challenges still to be solved. However, the prospective gains are definitely appealing for the industrial field. It is foreseeable that, as the more abundant conceptual research points at possible solutions to the practical hurdles, in time an increasing
number of solutions will be proposed, attempted and validated, thus unlocking the advantages that Continuous Experimentation can bring thanks to real-world data-driven software evolution.

7.2. Future Work

As future effort a design study demonstrating a full experimentation cycle is currently in its starting phase. The goal is to showcase a prototypical software experimentation procedure conducted on an automotive platform. The study is meant to show the feasibility of the approach, starting from the initial software deployment to the systems, to a software variant deployment and execution, data collection, result analysis, and final best-variant adoption.

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| Olsson H. H.            | to embedded systems: Industry and research perspectives               | Processing                                   |       |                 |
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|                         |                                                                      | Processing                                   |       |                 |

Table 4: Results from the literature investigation