INDUSTRIAL PERSPECTIVES ON THE ADOPTION OF VIRTUAL TESTING

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ABSTRACT

This research aimed to gain insight into current practices and challenges with respect to the adoption of virtual testing and integration with physical testing in product development processes. A focused workshop investigated industrial perspectives on adopting virtual testing and current challenges. This paper reports the findings from the workshop in which representatives from a range of industries explored how virtual testing is used to support physical testing in their different contexts. This paper discusses the current challenges industries face in adopting virtual testing and changing role of physical testing, with reference to recent literature on physical and virtual testing and supported by an earlier empirical case study. This paper reports areas where more research is needed to support industries in overcoming these challenges.

Keywords: New product development, Digital / Digitised engineering value chains, Decision making, virtual testing, phisical testing

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1 INTRODUCTION

Manufacturing industries are undergoing massive transformation due to the introduction of new technologies (Mamasioulas et al., 2020) and new requirements to meet sustainability targets (Mishra, 2022). In response, products and product development processes are necessarily being restructured, and testing will be an essential part of this restructuring to ensure that responses to external and internal pressures are appropriate. But, despite being intertwined with design throughout the development process, testing is often an overlooked activity and its importance needs to be more explicitly recognised (Tahera et al., 2019).

Managing physical testing activities in product design and manufacturing brings contradictory challenges. On one hand, the need for physical testing increases as companies introduce new technologies into their products to meet sustainability targets, especially for product validation and quality assurance. For example, the UK Industrial Decarbonisation Strategy highlights the need for enhanced testing across different uses and stages of new technologies, including low-carbon hydrogen production and heat recovery (HM Government, 2021). On the other hand, digitalisation supports sustainable design and manufacturing, so this drives the move towards reduced physical testing and more digital testing, also known as *virtual* testing. Also, physical testing is often costly, so there is a critical trade-off in reducing cost of physical testing without compromising quality, especially for radical emerging technologies which require comprehensive testing.

There is a trend in industry towards approaching testing differently, with an aim to cut testing costs, even in safety critical industries that have traditionally depended on physical testing, such as aerospace. For example, spacecraft manufacturer SpaceX has shifted its prototype testing early with its "fail-fast, fix-fast approach" to speed up the development process (Palmer 2021). Other organisations are complementing and reducing physical testing for certification using analytically based methods and tools. For example, NASA has published a roadmap for aircraft certification by analysis, which addresses how to obtain results for certification compliance that have traditionally been acquired using physical testing (Mauery et al., 2021). They claim that this will streamline the product certification testing programs at a lower cost, while maintaining equivalent safety levels and reducing the impact of schedule delays.

To investigate industrial perspectives on adopting virtual testing and current challenges, a focused workshop was conducted. This paper reports the workshop findings and discusses these with reference to an earlier case study (Tahera, 2014) and recent literature on physical and virtual testing. During the workshop, representatives from a range of industries explored how virtual testing is used to support physical testing in their different contexts. The aim was to gain insight into current practices and identify challenges with respect to the adoption of virtual testing and integration with physical testing processes.

The next section provides a brief overview of the adoption of virtual testing from the perspective of the academic literature, then, Section 3 provides a description of the workshop, and the methodology used to analyse the workshop data. Section 4 gives an overview of three scenarios that were represented at the workshop, each associated with different manufacturing industries, and Section 5 presents findings from the workshop, with respect to these scenarios. Section 6 discusses four key questions that emerged from the workshop, and finally Section 7 concludes the paper with a summary of its findings.

2 BACKGROUND

Traditionally, testing is a physical activity and includes, for example, materials and component testing for mechanical performance, through to whole system testing against customer requirements (O'Connor, 2001). But physical testing is often time-consuming and extremely costly, for example accounting for 30-50% of development costs in automotive or aerospace industries (Tahera et al., 2019). Also, physical testing can only consider a limited number of variables and operating conditions (Zorriassatine et al. 2003), and only within a controlled environment (Khalaf, 2006). This limits how and when physical testing can be used in the product development process, reducing opportunities to validate performance against customer requirements (Donà and Ciuffo, 2022). A critical challenge in manufacturing is how investment in physical testing can be reduced without compromising quality, especially when radical emerging technologies require a comprehensive assessment to ensure their capability and develop confidence in their potential performance.

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Virtual testing offers an alternative approach that reduces the amount of physical testing needed in product development processes (Huizinga et al., 2002). By taking advantage of digital technologies such as computer-aided design (CAD), computer-aided engineering (CAE), virtual reality (VR), augmented reality (AR), haptic prototypes, etc., virtual testing offers a simulation of reality in which the behaviour of virtual prototypes can be assessed (Camburn et al., 2017). This range of digital technologies creates opportunities to interrogate key design aspects using small scale (digital) representations and which can significantly increase design knowledge and confidence and reduce uncertainties (Hoppe et al., 2007). Virtual testing is useful for evaluating designs early in product development processes when physical prototypes are difficult and costly to produce (Kharul et al., 2010), and when it offers opportunities to prototype multiple iterations that can inform design decisions (Camburn et al., 2017). But it does require assumptions, about materials properties and/or the nature of boundary conditions etc., which may not be accurate (Ostergaard et al., 2011).

Virtual testing can reduce product development time and cost because it allows engineers to evaluate designs in hours rather than months, without the need to produce costly physical versions of designs (Huizinga et al., 2002). Because of this, virtual testing can increase the scope of testing scenarios that can be covered in a product development process (Tahera et al., 2019). This value of virtual testing is recognised across many industrial sectors, for example in product design (Tao et al. 2018), aerospace (Ostergaard et al., 2011) and nuclear (Popov et al. 2021) industries.

However, despite the benefits of virtual testing and even with the increased availability of advanced digital technologies, physical tests cannot be disregarded. Rigorous physical testing regimes can be essential in industries, such as aerospace, where certification requires that designs meet regulatory and safety standards (Maropoulos and Ceglarek 2010). Physical testing is also necessary for validating the outcomes of virtual testing, to ensure that data created from virtual prototypes reflects real-world behaviour of physical prototypes (Donà and Ciuffo, 2022). But this exchange is not one-way, and results from virtual testing can also inform the design and setup of physical tests (Remedia et al., 2017). Such integration is becoming common and is often formalised within product lifecycle management (PLM), in particular in the product data management (PDM) component, which is concerned with product data, created and used throughout a product lifecycle (Stark, 2020).

In recent years, the concept of the "digital twin" has emerged, which has the potential to improve the integration of physical and virtual data in product lifecycle management. In general, a digital twin is a digital counterpart of a physical product that can be used for simulation, testing and maintenance assessment, but the concept attracts a variety of definitions across industry and academia, from simply a virtual representation of a product, through to a virtual dynamic model in a virtual world that is connected to, and can simulate the behaviour of, a physical product in the real world (Lo et al., 2021). Digital twins support integration of physical and digital testing by offering opportunities to link data derived from virtual and physical models. For example, virtual data from conceptual stages can inform physical design, and in-use data can inform next generation development. However, they also give rise to new challenges, for example in managing complex data flows and in data privacy (Lo et al., 2021).

3 METHODOLOGY

We conducted a 3-hour online workshop in June 2022, titled “Physical testing in the era of sustainable manufacturing and digital transformation: how to manage testing better?”, with the aim to investigate the challenges industries face as they consider the adoption of digital technologies and virtual testing. The workshop was organised to provide an opportunity to consult with UK-based industrial representatives, each with between five- and thirty-years' experience, to develop a more comprehensive understanding of current practices, to identify current challenges, and to discuss possible solutions that benefit both industry and academic research. The objectives of the workshop were to gain a collective view from academics and industrial experts from the manufacturing industries of the critical role of physical and virtual testing in product development and to obtain a detailed understanding of the factors that affect testing decisions in new product development.

The workshop was delivered by videoconference and attended by eighteen participants. Six participants were from UK-based sectors: automotive, aerospace, household appliance manufacturer, oil and gas industries, and software industry. Also, twelve academics from the UK, USA and Europe attended. The workshop was conducted in the style of a focus group in which “a small number of people in an informal group discussion, ‘focussed’ around a particular topic or set of issues’ (Silverman, 1997). In order to

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facilitate deep discussion, the workshop attendees were divided into three breakout rooms in parallel 30-minute sessions for the first part of the workshop. Each breakout room was selected to have a mix of industrial and academic participants and was facilitated by an academic with relevance expertise. The starting questions for discussion in each breakout room were "*When does testing happens in new product development?*" and "*What are the current challenges?*" and this led naturally to a broad discussion around physical and virtual testing. In the second part of the workshop, all the participants collectively discussed the question, "*What are the challenges in the digitalisation of the testing process?*".

The workshop was recorded and transcribed using Microsoft Teams, and data were analysed using an open coding method to identify patterns in the data (Miles and Huberman, 1994). Tags were used to assign meaning to the descriptive responses from the workshop and these were then clustered into themes and subthemes. The initial coding was performed independently by three of the authors to avoid individual bias and each author clustered the concepts into between four and six themes. They then jointly refined the results into seven commonly agreed themes that will be the focus of this paper: *integration; responsibility; uncertainty; data source; change; culture* and *purpose*.

4 TESTING SCENARIOS

Workshop attendees brought a wide range of experience of product testing from different industries and presented a range of different challenges. The challenges presented were different for different industry sectors, so three exemplar scenarios have been developed to illustrate the testing challenges faced in industry. Each scenario is based on testing challenges identified by one or more companies in a single sector or several sectors facing similar challenges.

The first scenario relates to the household appliances sector which is fast moving, with new products being constantly introduced, often incorporating new technology. The product development cycle for household appliances is very short, meaning that there is limited time for testing. In addition to physical testing, products are sent for user trials and shared in focus groups. User data is gathered and shared internally to improve the product. Historically many prototypes would be built and tested during the product development process, but there is now a push towards using fewer prototypes, considering product verification from the concept stage, simulating first and using more virtual testing.

The second scenario relates to vehicle manufacturing (broadly including automotive and aerospace), which is experiencing rapid change due to the introduction of alternative propulsion technologies. In automotive, engine test cycles have often not changed for many years, but the transition to hybrid and electric propulsion is changing the testing requirements and manufacturers have less experience of how their customers interact with new propulsions systems. There is an increased focus on reliability engineering and modelling failure mechanisms through the product development process, aiming to identify issues earlier in the development process and reduce dependence on physical testing. Modern vehicles have engine management systems that record data while the product is in use, and in the future manufacturers could utilise this data more effectively to understand how their customers interact with the technology. Aerospace is also investigating alternative propulsion technologies. This sector is often highly regulated, and safety critical and the products are extremely complex, which makes testing very costly and challenging. Currently physical testing is required for certification, but simulation is also used extensively to model many aspects of a vehicle's design. Simulation is widely used in the design process, but it is not currently possible to model all aspects of a product together to simulate an entire vehicle at a high level of detail.

The final scenario relates to the energy sector which is characterised by very large infrastructure projects that can have extended lifecycles of 100 years or longer. This sector is also subject to rigorous safety requirements, and it is extremely challenging to perform tests that can predict product performance over such an extended lifecycle. The cost of failure can be extremely high, and the testing challenges in this industry can limit innovation due to an unwillingness to move to new technologies with unknown risks. Through life monitoring is a possible solution to managing these risks, allowing prediction of failures in service based on monitoring data.

Comparing the three scenarios identified in the workshop and the sectors they represent, the key differences between them can be summarised in terms of product lifecycle, complexity and risk, as shown in Table 1.

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Table 1. Summarising key differences in testing scenarios

	Appliances	**Vehicles**	**Energy**
Product lifecycle	Short	Medium to Long	Very long
Complexity	Medium	High	Medium to High
Risk	Low to Medium	High to Very high	High to Very high

5 FINDINGS

Despite the differences between these three scenarios, there were notable parallels in the issues raised by the workshop participants with respect to the adoption of digital testing. A summary of the issues raised in the workshop and the identified recurring themes are arranged in Table 2. Taking a holistic view of the workshop findings, four overarching concerns emerged that will be discussed in more detail in the next section.

The superscript numbers in Table 2 identify how the different issues raised in the workshop relate to the four numbered concerns which are:

1. Lack of shared understanding of testing terminology
2. What is the scope of virtual testing?
3. Challenges of adopting virtual testing
4. The changing role of physical testing

Table 2. A summary of issues raised in the workshop

<table>
<tr><th rowspan="2">Themes</th><th colspan="3">Scenarios</th></tr>
<tr><th>Appliances</th><th>Vehicles</th><th>Energy</th></tr>
<tr><td rowspan="4">Integration</td><td colspan="2">How to ensure knowledge isn't lost in translation between departments, tools, etc [1]</td><td rowspan="4"></td></tr>
<tr><td colspan="2">Lack of common understanding of testing terminology [2]</td></tr>
<tr><td rowspan="2"></td><td>Combining models results in emergent behaviour [2]</td></tr>
<tr><td>Need to bridge the gap between physical and virtual tests [4]</td></tr>
<tr><td rowspan="2">Responsibility</td><td></td><td>Managing multi-disciplinary models [3]</td><td></td></tr>
<tr><td colspan="3">Who maintains the data, and how is it made available [3]</td></tr>
<tr><td rowspan="5">Uncertainty</td><td rowspan="2"></td><td>Complexity of virtual testing, how to quantify the unknown [3]</td><td>Regulations for new technology are unspecified [3]</td></tr>
<tr><td colspan="2">Lack of data for new technologies [3]</td></tr>
<tr><td>How to capture all use-cases [4]
Prefer to re-test than trust external data [4]</td><td>How to decide what to test physically [4]
Continuous testing in-service reduces risk [4]</td><td></td></tr>
<tr><td rowspan="2"></td><td colspan="2">How can reliability be demonstrated via limited testing [4]</td></tr>
<tr><td></td><td>How to reliably test for long-life products [4]</td></tr>
<tr><td>Data Source</td><td colspan="2">Incompatibility of data from different sources, e.g. models, software, etc [2]</td><td></td></tr>
<tr><td rowspan="4"></td><td></td><td>Need a systematic way to capture data [3]
Metadata is vital [3]</td><td></td></tr>
<tr><td></td><td colspan="2">How to extrapolate data from the lab to the real-world [3]</td></tr>
<tr><td colspan="2">Useful data from user-trials/in-use [4]</td><td rowspan="2"></td></tr>
<tr><td>Designing tests to ask the right questions [4]</td><td>In-service can raise issues not identified in testing [4]</td></tr>
</table>

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Change		Lack of knowledge about virtual testing results in resistance to change [3]	Difficulty moving to new technology if lifelong behaviour not verified [3]
	Rapid time to market makes testing challenging [4]	Move verification, validation, and failure mode analysis earlier in process [4]	
	A move towards virtual testing to minimise physical testing [4]	Historically verification engineers located close to manufacturing [4]	
Culture		Lack of common language between teams [1]	
	Definition of virtual test is very broad [2]		
	Lack of confidence in virtual tests, wait for physical results [3]	Virtual testing should be in first stages [3]	
	Duplication of physical tests [4]	Using inappropriate legacy test cycles [4]	How to extrapolate results over long product life [4]
	Too much confidence in physical results [4]	More early physical testing to gain knowledge [4]	
	Who owns component tests [4]	Understand when testing is most valuable [4]	
Purpose		What can you learn from testing [2]	
		Emergent behaviour creates knowledge beyond purpose of the test [3]	
	Designing tests to ask the right questions [4]	In-service can raise issues not identified in testing [4]	

6 DISCUSSION

The four concerns that emerged from the workshop findings, warrant deeper consideration, and these will now be considered in turn.

6.1 Lack of shared understanding of testing terminologies

A key challenge reported by the industry participants is a lack of common testing vocabulary and terminology both within organisations and the wider supply network. Testing groups might comprise mathematicians, engineers, technicians and other roles who use heterogeneous testing terminologies. For example, it was quoted by one of the workshop participants that "*people interchangeably use verification and validation, while these two terms have significantly different purposes and outcomes*". This means a lack of agreement about the conceptual understanding of the terminologies used. This issue can make it challenging to integrate testing data across the different product development stages. Which, in turn, causes significant issues in trust/confidence in testing data within the supply chain. So, the question arose, "*how to bridge the language gap between teams of hardcore engineers, CAE teams, designers, virtual and physical test engineers and technicians?*".

6.2 What is the scope of virtual testing?

It was found that the definition of a virtual test and its scope are broad in all three scenarios. During the workshop, virtual testing was used to refer to a range of tools for interrogating a design, including mathematical models, CAE analysis, modelling and simulation, and digital twins. Even hand calculations were offered as an example of virtual testing. Clearly, the term "*virtual testing*" means different things to different people. Also, the terms “*CAE analysis*” and “*virtual testing*” are often used interchangeably in the literature. A lack of agreed definition of virtual testing can create confusion between teams involved, and so limit the usefulness/use of virtual testing results making it harder to integrate with other activities, such as design analysis and physical testing.

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Similarly, while virtual testing is a well-used term used in academia, a clear definition is not found in recently published academic literature. Older definitions can be found, e.g. from the field of Electrical and Electronics: Helmreich & Reinwardt (1996) defines "*virtual test, i.e. developing, debugging and verifying a test program in a simulation environment rather than on a physical tester*" and Lu et al. (2009) define virtual testing as "*developing and debugging a test with simulation models of the device under test (DUT)*". A broader view of virtual testing, in the field of engineering design, was presented by Huizinga et al. (2002) "*closer cooperation between designer, analyst and tester are necessary, and right from the start of the engineering phase, the reality has to be simulated by performing complex calculations and analyses using advanced hardware and software. This is referred to as 'virtual testing'*". Similar to the workshop findings, the definitions of virtual testing found in academic literature refer to a range of activities, from complex calculations to any advanced analysis done in a virtual environment using computer models and simulation.

We can attempt to define "*virtual testing*" and establish its relationship with CAE analysis with reference to an earlier study based in on an engine manufacturing company (Tahera 2014). According to the study, early CAE analyses create design briefs based on requirements. Further developments of these CAE analyses are performed almost in parallel, and in an iterative way, with design, to define the scope of the design activity. Finally, advanced CAE and simulations are performed once the initial design is completed, and design data and information are released to suppliers for procurement of prototypes for physical testing. This latter type of analysis examines whether a design meets the specifications and requirements of that phase of design and serves the same purpose as physical testing or complements and assists physical testing. Differentiation between these terms can be described as: "*virtual testing is all about simulating the test conditions, which is the history of knowing that the product worked. Whereas CAE is all about trying to prove that the product will meet the requirements that the customers, and legislations are asking*", (Tahera 2014). A similar definition by Jones and Simon (2002) complements our understanding from the case study, which describes *"simulation which is performed after a design concept is established leans toward the definition of virtual testing, meaning that in-lieu of the simulation; it would be possible to build a prototype of the design and test it"*. This definition clearly indicates a distinct phase when the activities between CAE analysis and virtual testing differ, based on when the "*design concept* [is] *established* ".

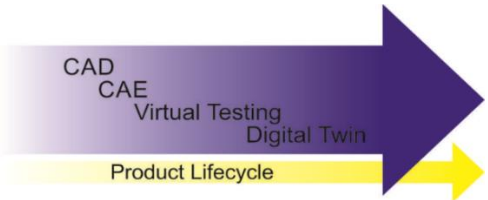

Figure 1. Digital modelling through the product lifecycle

Figure 1 illustrates this evolution from a CAD model, analysed using CAE through to virtual testing and digital twins. As the product development progresses, the objectives, related conditions and depth of analyses differ, and it is essential to understand the difference between analysis and testing for effective communication and data integration. Integrating CAD and CAE as separate but parallel concepts, that develop into virtual testing, which alongside physical testing, can inform and contribute to the development of a digital twin of a physical product.

6.3 Challenges of adopting virtual testing

A few key challenges in adopting virtual testing were highlighted related to i) the culture and people: some companies find it challenging to adopt virtual testing due to the lack of trust in virtual test results, primarily those who historically relied on physical tests; ii) uncertainty in data: due to lack of field-data with new technology and lack of data to build virtual models; iii) how to quantify uncertainty in virtual testing results and the need for physical testing to correlate and validate the virtual testing results; iv) the complexity of interdisciplinary simulation models and their integration: different models are used for different purposes by different teams. Integration of these models to observe emerging behaviour is highly complex.

However, it was recognised that effective integration of virtual models brings advantages such as observing and understanding the underlying cause of emerging behaviours of a system, which may help identify risks and opportunities earlier in the design process. A workshop participant mentioned

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the importance of model integration, "*to understand whether it's something that we want to be able to control or whether something we want to be able to minimise because it's detrimental or whether we want to amplify it because it's beneficial".* But this raises further questions, for example if unexpected behaviours are identified through virtual testing, how can there be confidence in the results, and who takes responsibility for those results? Similar challenges were raised with respect to data responsibility; virtual testing and computational analysis produce enormous amounts of data, so who maintains data? And how can the data be made available to those who need it, when they need it?

6.4 Changing role of physical testing

Some challenges were discussed that result from relying on physical test data only: i) a physical component test can deal with only limited variables and use conditions and is done in a controlled environment. A physical test cannot always be comprehensive enough to include all the operating conditions. So how to capture all use cases in physical testing, e.g. from different users, to validate the product? ii) there is a lack of trust in physical test results when done externally, such as by suppliers, and there is a tendency to re-test to create their own physical test data, which creates frustration over duplication of test data. iii) data from service finds issues not picked up in testing. iv) tension due to limited physical tests as a result of the development cost and time, combined with the requirement to demonstrate the reliability of new technologies with limited testing. Introduction of new technologies and new product development adds more challenges, such as lack of data with new technologies to make decisions on what to test physically, lack of data to understand how customers interact with new technologies, lack of standards and guidelines regarding regulatory environment and link to requirements to know what to test physically. Also, several emerging roles of physical testing were identified in the workshop and were considered essential:

- *A reliable data source to create virtual models and model validation:* This is particularly true for new technology since the physical testing of early prototypes is the only quick and reliable data source for virtual model building and validation. There is a trend toward early physical testing to collect data and gain learning through early prototype testing. Previous findings also record that a company may carry out a physical test for a baseline product, the standard product, without adjustments for specific needs. As described by Tahera (2014): "*the baseline product definition is physically tested, and that information is fairly adequate for simulation to run for multiple variables for longer times to find the optimum setup. Then a physical test is required to validate the product as well as simulated results".*
- *Moving left in the V-model:* In the vehicle scenario, it is reported that there is a recent push to move the verification and validation aspects earlier in the product development process. With reference to the V-model (Bauer et al., 2022), this was referred to as moving "*left*", termed as "*shift left*". Since testing is a crucial verification and validation method, this agile approach aims to front-load testing earlier in the development process. The appliance scenario highlighted a similar approach: "*we have got early engagement in terms of getting people thinking at the concept stage. How are we going to verify?*" Another force to shift towards early prototype testing was to reduce epistemic data uncertainty due to lack of knowledge and lack of data either for model building or learning.
- *For identifying Failure Modes for new product development:* In the verification and validation plan process, failure mode and effect analysis is a standard practice, e.g. to identify how a failure may happen and how that can be avoided through design and testing. Determining failure modes for new technology without prior experience and data is difficult. So, baseline testing is necessary to investigate the "*true mode of failure*" or to "*rank the failure mode correctly*". And this emphasises the previous point of shifting physical testing earlier in the process. In the vehicle scenario, it was noted that there is "*a move towards reliability engineering to model failure mechanisms throughout the product development process rather than test at the end of development."* Also, alternative sources are used for gathering data, such as user trials and focus groups, recording data from products-in-use and continuous testing in service to reduce risk.
- *Closer integration of virtual and physical testing:* It was highlighted in all scenarios that a close integration of virtual testing can reduce the challenges of physical testing identified above. Especially when physical testing cannot be comprehensive enough to include all the operating conditions and testing multiple physical prototypes to cover a wide range of use-case is

economically unfeasible; creating multiple models and running them in different scenarios in a virtual environment is possible with a fraction of the cost. Through virtual testing, optimum boundary conditions and critical use conditions that need physical testing can be recognised. But to build such a comprehensive virtual model, especially for new technologies, it is necessary to have reliable data from physical tests. So, the roles of virtual and physical testing and how they interplay in different stages of the product development process need to be clearly identified to enable their effective integration.

7 CONCLUSIONS

Not all industries have the same enthusiasm for virtual testing, nor will they adopt virtual testing at the same pace. But, the advantage of virtual testing has been recognised in many industries, where the move towards the digitalisation of the testing process is taking place. However, comprehensive physical testing is also necessary to introduce new sustainable technologies into a product for learning technological capability, validation, and certification. The balance between virtual and physical testing is a challenge for industry. This research was limited in scope, but clearly identified that for all scenarios considered, and the industrial contexts they represent, there is a need for closer integration of virtual and physical testing. It is necessary to systematically plan these activities throughout the product lifecycle to take advantage of both approaches. To achieve this, more research is needed: i) to support the integration of teams by breaking the language and cultural barrier between teams to establish trust in virtual and physical testing data, ii) to identify the data thread from different sources throughout the lifecycle including product use and maintenance, iii) to support integration of models and interoperability between tools, models, data (produced both from digital models and physical test), and iv) to enable effective planning of virtual testing and physical testing throughout the product development in order to maximise the benefits.

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