# VIRTUAL COMMISSIONING IN MACHINE TOOL MANUFACTURING: A SURVEY FROM INDUSTRY

# LA PUESTA EN MARCHA VIRTUAL EN LA FABRICACIÓN DE MÁQUINAS HERRAMIENTA: ENCUESTA INDUSTRIAL

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Received: DD/MM/AA – Reviewed: DD/MM/AA -- Accepted: DD/MM/AA - DOI: https://dx.doi.org/10.6036 (To be completed by Editor)

*ABSTRACT:*

*Virtual commissioning has acquired a major interest with the introduction of Industry 4.0. It is demonstrated that virtual commissioning can significantly reduce the commissioning time, error rate and costs. However, industry is still experiencing difficulties with the integration of these new technologies. This paper is one of the first empirical surveys conducted in the industry that aims at understanding the challenges and current practices with respect to virtual commissioning, with special focus on the machine tool manufacturing sector. The survey contextualizes the practice of virtual commissioning and the digital twin in industry, and benchmarks the results with academia, in which main gaps are identified.*

*Keywords: empirical survey, virtual commissioning, digital twin, machine tool manufacturing, testing*

RESUMEN:

La puesta en marcha virtual ha adquirido un gran interés con la introducción de la Industria 4.0. Está demostrado que la puesta en marcha virtual puede reducir significativamente el tiempo de puesta en marcha, la tasa de errores y los costes. Sin embargo, la industria sigue teniendo dificultades con la integración de estas nuevas tecnologías. Este estudio es una de las primeras encuestas empíricas realizadas en la industria que tiene como objetivo comprender los desafíos y las prácticas actuales con respecto a la puesta en marcha virtual en el sector de la fabricación de máquinas herramienta. La encuesta contextualiza la práctica de la puesta en marcha virtual y el gemelo digital en la industria, y compara los resultados con el mundo académico, en el que se identifican discrepancias significativas.

Palabras clave: encuesta empírica, puesta en marcha virtual, gemelo digital, máquina herramienta, validación y verificación

## FUNDING

This work is part of the DiManD Innovative Training Network (ITN) project. DiManD ITN is a European Training Network (ETN) programme funded by the European Union through the Marie Sktodowska-Curie Innovative Training Networks (H2020-MSCA-ITN-2018) under grant agreement number no. 814078.

## 1. INTRODUCTION

Conventionally commissioning is carried out during the last phase of the development process [1]. The development of a machining system involves multiple engineering disciplines such as dynamics, kinematics, software and automation. These engineering disciplines however have been traditionally working in silos and consequently, discrepancies and errors are encountered for the first-time during commissioning. This increases time to market and hence costs associated to it [2].

Virtual commissioning has been a subject of study for the past two decades. It has been defined as the practice of using virtualisation and simulation technologies that represent the physical plant and/or controller on a virtual environment to validate the behaviour of the manufacturing system. One of the key aspects is that it carries out a series of verification tasks early in the development process [1]-[2] between multiple engineering disciplines [3], [2] in contrast to conventional commissioning (Fig. 1).


ISSN: 0012-7361 eISSN: 1989-1490 / DYNA Vol.96 nº6 DOI: https://doi.org/10.6036/10244

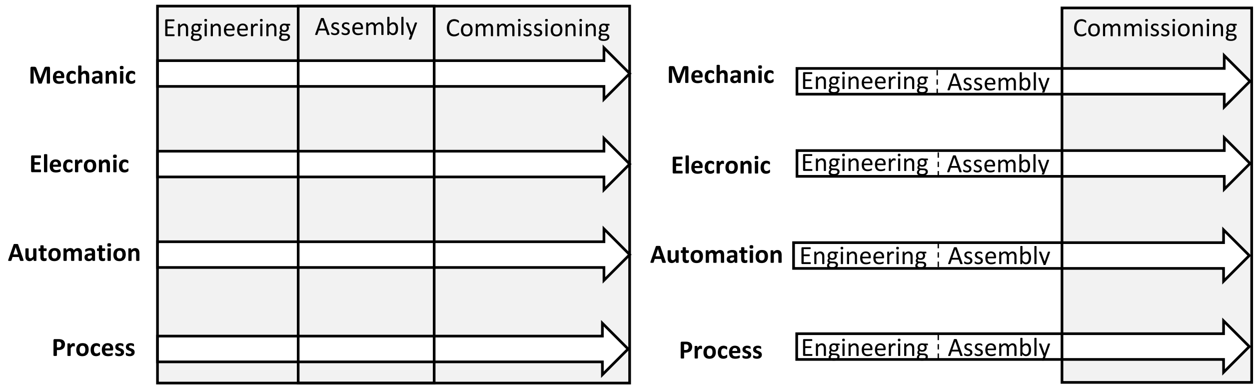


*Fig. 1. Virtual Commissioning vs Conventional Commissioning*

As seen in Fig. 1, virtual commissioning is carried out in a collaborative way among mechanical, electronic, automation and process engineers, in which verification tasks can occur during the whole development process. Engineers can test the system virtually before the physical system is built, and therefore, discrepancies can be found early in the development process. This significantly reduces commissioning time and errors.

Virtual commissioning can reduce the commissioning time up to 75% as indicated in [4]. Moreover, M. Schamp et al. [5] performed a digital twin-based virtual commissioning, reducing the debugging time by 75%, while improving the quality up to 31%. Similarly, S. Xueming et al. introduced a digital twin-driven approach for assembly commissioning, indicating a reduction in the assembly time by 37.5% [6].

The use of the virtual commissioning and digital technologies have also been under study for testing reconfigurable Cyber Physical Systems (CPSs). A recent study carried out by A. Talkhestani and M. Weyrich [7] exploited these technologies for testing the reconfiguration of an intelligent warehouse. The results demonstrated a reduction in reconfiguration process time by up to 58 percent with the use of the digital twin. A. Talkhestani and M. Weyrich attention was focused on the provision of virtual commissioning to shorten the reconfiguration of a production system. On this matter, R. Alt et al. [8] focused on the concept of virtual commissioning to simulate the newly configured system of a fluid power machine and automate its integration in the context of plug and produce. Similarly, W. Hofmann et al. [9] described a simulation-based virtual commissioning for a modular and reconfigurable plug and play conveying system.

Despite the benefits of virtual commissioning to shorten the commissioning time and effort, while improving overall quality, there is still lack of industrial practices in the market. Hence, this study aims at studying the industrial readiness, as well as the main barriers the industry is facing when implementing such technologies. To the best of the author's knowledge, little attention has been paid to the user experience. In fact, there are few empirical studies in the literature regarding this matter. One of the fewest empirical surveys in the industry is carried out by L.F. Durao et al. [10], which conducts an interview with industrial representatives in Brazil. The survey shows that most of the companies implemented the digital twin technology to build solely a simulation model of their production lines. According to the study, the major challenge lies in the implementation of the digital twin, in which the main barrier is the integration of data to build a high-fidelity digital twin with real time control capability.

Therefore, this study presents an empirical survey to assess the current industrial readiness, needs and challenges that the industry is facing today, with special focus in the machine tool manufacturing industry.


ISSN: 0012-7361 eISSN: 1989-1490 / DYNA Vol.96 nº6 DOI: https://doi.org/10.6036/10244

## 2. – SURVEY DESCRIPTION

This survey was carried out by following the overall structure and methodology presented in [11].

### 2.1.- OBJECTIVES AND RESEARCH QUESTIONS

The empirical survey attempts to address the existing issues and challenges the industry is facing with respect to virtual commissioning in contrast to academia. The objective of this study is to bring awareness of the practice of virtual commissioning and the use of the digital twin in the manufacturing industry, and to identify existing gaps between industry and academia for further research on this matter. Hence, the following research questions (RQ) were defined to benchmark the current industrial practices with academia.

The first set of questions focuses on the practice of virtual commissioning in industry to obtain the user experience and expectations about its practice. This will help to assess the current industrial readiness for virtual commissioning solutions, and to identify the existing needs and difficulties the industry is facing these days.

- RQ1.1: What are the main challenges in traditional commissioning?
- RQ1.2: What is understood by “virtual commissioning” in the industry?
- RQ1.3: Does virtual commissioning involve different engineering disciplines?
- RQ1.4: Is virtual commissioning carried out at earlier stages of the development process?
- RQ1.5: What are the perceived benefits of performing virtual commissioning?
- RQ1.6: What are the main challenges faced with virtual commissioning?

The second set of questions encompasses the digitisation of industry and the technological readiness for virtual commissioning, focusing on the use of the digital twin. The end goal is to assess the technological and industrial readiness in terms of the use and/or implementation of the digital twin, and to identify the main challenges in Industry.

- RQ2.1: What is understood by a digital twin?
- RQ2.2: What is the degree of implementing of the digital twin in industry?
- RQ2.3: What are the main challenges faced with the digital twin?
- RQ2.4: What are the perceived benefits of the digital twin?

Finally, the survey addresses the testing practices during commissioning, the level of automation of current industrial practices, and the main challenges faced when testing CPSs during commissioning.

- RQ3.1: What are the tests carried out during the commissioning process?
- RQ3.2: Are the carried-out tests automated?
- RQ3.3 Is there a need for automating tests?
- RQ3.4: What are the main testing challenges faced in the development and operation of a machine tool?

### 2.2.- TARGET POPULATION

Our target population consisted of industrial practitioners, and academic lecturers and researchers who have worked on virtual commissioning projects. The surveyed population was limited to the machine tool manufacturing industry, including well known representative companies in this sector.

The survey was firstly initiated at IDEKO, the research centre of Danobat Group, as well as a member of Mondragon Cooperative Corporation (MCC), in northern Spain. The initial set of actions included the assessment of the answers to measure the quality of the questions and identify any additional question required to address the research questions. Thus, the questions were rewritten and shared afterwards within the members of MCC, and later expanded to a wide range of companies, including international ones, all within the machine tool sector (i.e. Siemens, Fagor, Volvo, etc.). Finally, the survey was carried out among the beneficiaries and early-state researchers of the DiManD Horizon2020 project to benchmark the results of the industry with


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academia. A total of 31 organisations took part in the survey, in which a total of 87 contacts were reached out. All the organisations that took part on the survey are illustrated in Fig. 2, classified by the type of organisation: research centre (highlighted in black), industrial company (highlighted in grey) and academia (highlighted in blue).

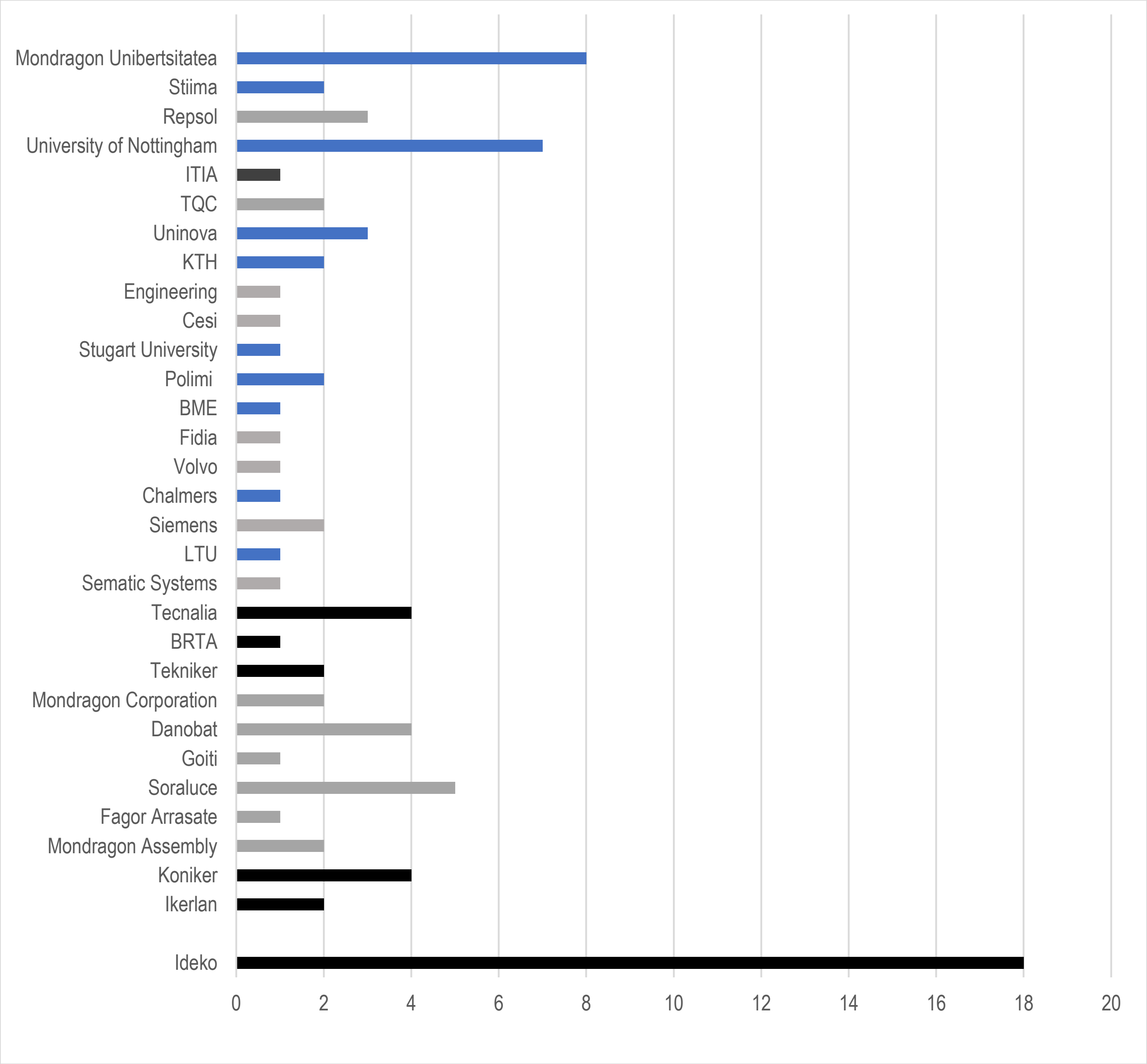


*Fig. 2. Surveyed participants in research centres, companies, and academia*

## 2.3.- STRUCTURE OF THE SURVEY

The survey was divided in five groups, covering background, organisational information, and technical questions related to the research topics highlighted in Section 2.1, i.e. virtual commissioning, the use of the digital twin, verification and validation practices. As seen in Fig. 3, the survey consisted of 26 questions designed to address the research questions raised in Section 2.1.


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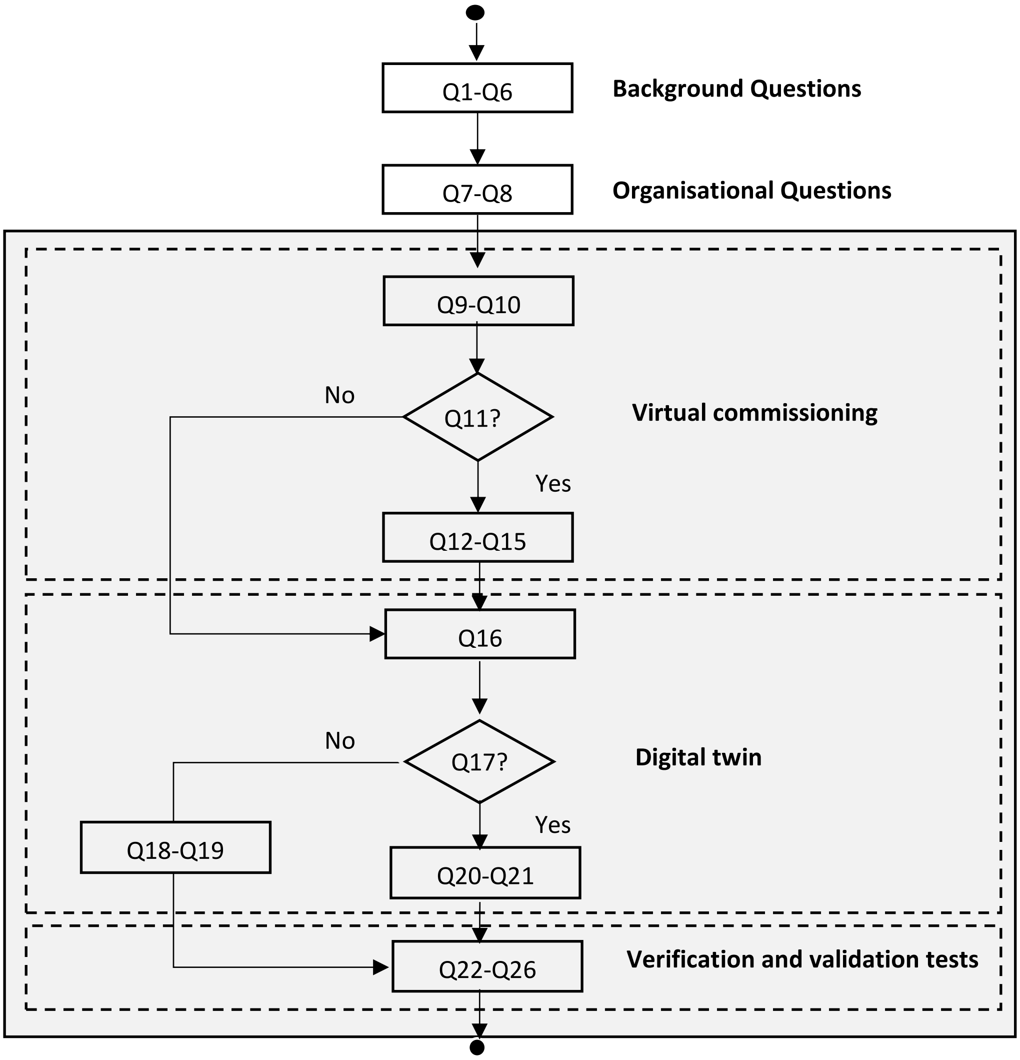


*Fig. 3. Structure of the survey*

- Background questions (Q1-Q6): it includes questions related to the gender, role in the company, years of experience within the organisation, years of experience in the machine tool manufacturing industry, background, and the expertise in terms of the use of technologies.
- Organisational questions (Q7-Q8): this refers to the organisation and the sector of the surveyed participants. The organisation could be a company, academia or research centre as described in Fig. 2.
- Technical questions: this block consists of 18 questions that aim to address the research questions regarding the practices of virtual commissioning, the use of the digital twin and testing practices during commissioning.
    - Virtual commissioning (Q9-Q15): this block of question addresses the first set of research questions (RQ1.1, RQ1.2, RQ1.3, RQ1.4, RQ1.5 and RQ1.6). However, some of the questions were conditional, based on the implementation of the virtual commissioning, hence, those questions could not be answered by all participants. This block includes questions about the concept of virtual commissioning, the main benefits and challenges, the purpose of its practice, engineering disciplines involved within the process, and the complexity of commissioning virtually.
    - Digital twin (Q16-Q21): this block addresses RQ2.1, RQ2.2, RQ2.3, and RQ2.4, and has also a conditional set of questions based on the degree of implementation of the digital twin. The questions encompass the definition of the digital twin, the main benefits and challenges and the goal of implementing the digital twin.
    - Verification and validation tests (Q22-Q26): this sort of questions addresses RQ3.1, RQ3.2, RQ3.3, and RQ3.4, and focuses mainly on testing practices, i.e. the testing methodology, involved engineering disciplines when testing, and the problems encountered during the development and operation of CPSs.



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## 3. – ANALYSIS AND RESULTS

A total of 26 participants responded the survey, in which 88% of them were male and 12% female. The participants were representatives of different backgrounds (23% mechanic, 23% electronic, 19% automation, 12% informatics, 8% ICT, 4% mechatronic, 4% industrial organisation, 4% telecommunications, 4% systems engineering). Most of them are experienced professionals with more than 10 years of experience (81% of participants), in which 50% of them have more than 10 years of experience in the machine tool manufacturing sector. However, we could not identify the individual companies due to the privacy and confidential reasons.

### 3.1.- RQ1.1 RESULTS

RQ1.1 addresses the challenges faced in traditional commissioning. Traditionally commissioning has been carried out at the end of the development process, and it has claimed that it is error prone as the system is not tested until everything is fully installed. RQ1.1 therefore, observes the industry and academic experience with regard to traditional commissioning. We asked the participants to select the most relevant issues when commissioning among the following options already raised in the literature [2]: time to market, little margin for error correction, unexpected issues due to errors from previous development stages, difficulties in testing the electrical system, and development costs.

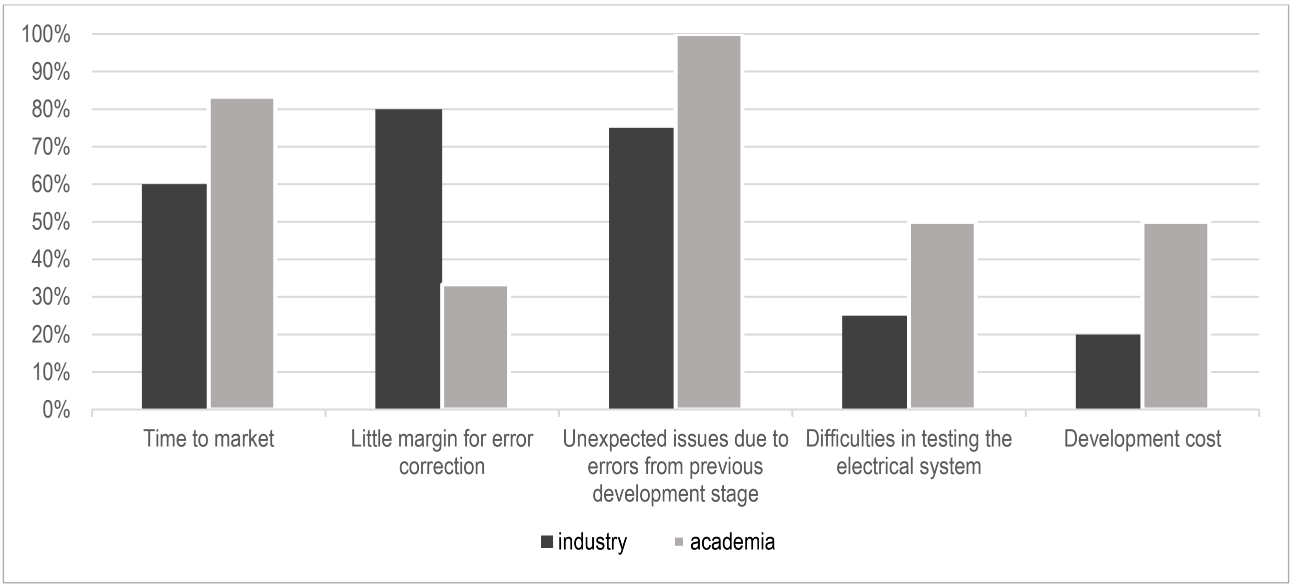


*Fig. 4. Challenges in traditional commissioning*

The results in Fig. 4 show the main challenges in traditional commissioning for both industry and academia, in which unexpected issues due to errors from previous development stages is the most critical one. Time to market seems to be also a big issue for the 80% of researchers and the 60% of industry practitioners. Moreover, the 80% percentage of the surveyed industrial participants claim that there is a little margin for error correction. This clearly opens up a real need for virtual commissioning to shorten time to market, reduce errors during the commissioning phase, and consequently, reduce overall costs due to time delays and unexpected issues.

### 3.2.- RQ1.2 RESULTS

As described in section 1, virtual commissioning is the practice of using simulation technologies to test system behavior with a virtual machine model before connecting it to the real system. However, virtual commissioning could happen at different testing levels based on the virtualisation solution: Hardware-in-the-Loop (real controller and virtual plant), Reality-in-the-Loop (virtual controller, real plant), Software-in-the-Loop (virtual controller and virtual plant). In this context, it is important to make sure


ISSN: 0012-7361 eISSN: 1989-1490 / DYNA Vol.96 nº6 DOI: https://doi.org/10.6036/10244

everyone uses the same terminology and shares the same conceptual definition. RQ1.2 therefore, addresses this issue by asking the participants to select the closes definition according to their virtualisation solution.

Furthermore, RQ1.2 also attempts at expanding its definition through the main capabilities offered by virtual commissioning: performing a series of collaborative verification tasks between different engineering disciplines and performing such tasks through the whole development process.

Fig. 5. Illustrates the definition of virtual commissioning according to the industry and academia. The Y axis shows the percentage of the population, whereas the X axis indicates the statements of virtual commissioning that were surveyed.

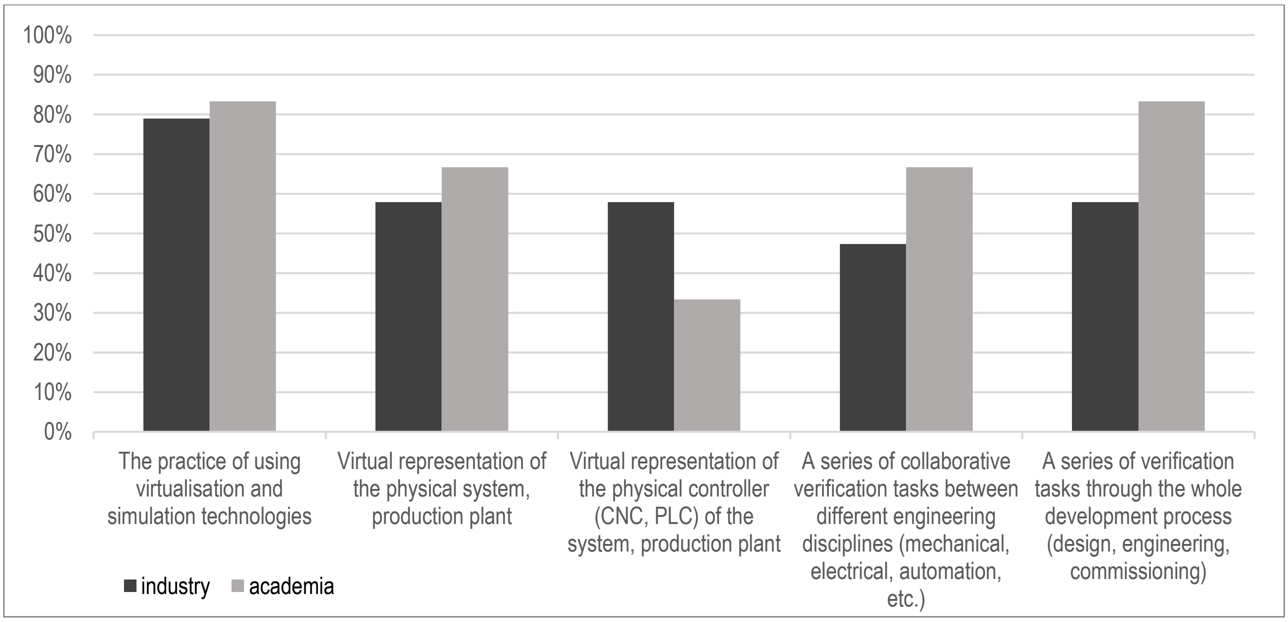


*Fig. 5. Virtual commissioning definition*

According to the results shown in Fig. 5, the 80% of the industry defines virtual commissioning mainly as the practice of using virtualisation and simulation technologies, in which 58% of them refer to the virtual representation of the production plant and/or controller. However, academia also highlights the capability to perform a series of collaborative verification tasks between different engineering disciplines through the whole development process, whereas only the 47% and 58% of the industry highlights these aspects. This indicates that there is still little awareness of the full benefits of virtual commissioning in the industry.

## 3.3.- RQ1.3 RESULTS

RQ1.3 addresses the statement defined in RQ1.2 as “virtual commissioning facilitates a series of collaborative verification tasks between multiple engineering disciplines”. In this regard, RQ1.3 examines current industrial and academic practitioners to acknowledge the involved disciplines during virtual commissioning (see Fig. 6). The involved engineering disciplines are shown in the X axis (mechanical, electronic, CNC control and automata, software, design, telecommunications, and systems engineers), whereas the Y axis indicates the percentage of the population for both industry and academia.


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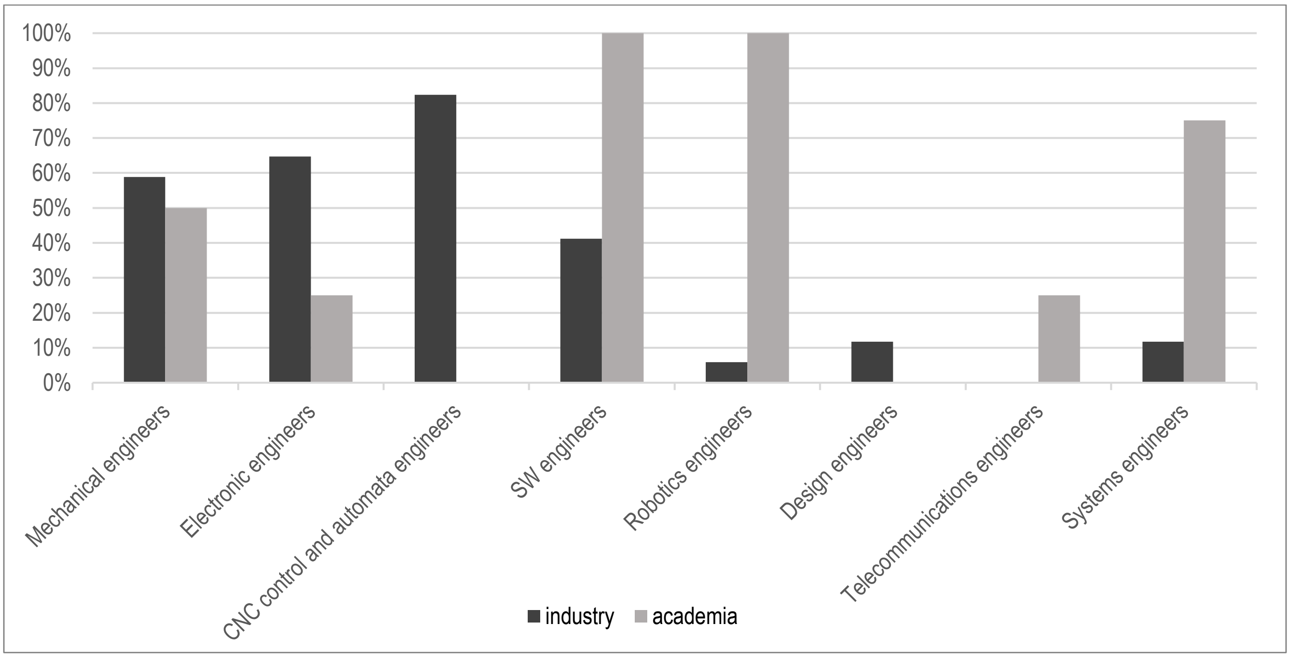


*Fig. 6. Virtual commissioning practitioners*

As seen in Fig. 6, virtual commissioning involves mainly CNC control and automation engineers (82%), as well as electronic (65%) and mechanical engineers (59%) in industry. On the contrary, all surveyed participants from academia believe that software and robotics engineers are key players when commissioning, where 75% of them also believe that systems engineers are required.

## 3.4.- RQ1.4 RESULTS

RQ1.4 addresses the statement defined in RQ1.2 as "virtual commissioning facilitates a series of virtual verification tasks through the whole development process". Hence, Fig. 7. illustrates the stages of the development process (X axis) in which virtual commissioning is mostly carried out according to the industry and academia.

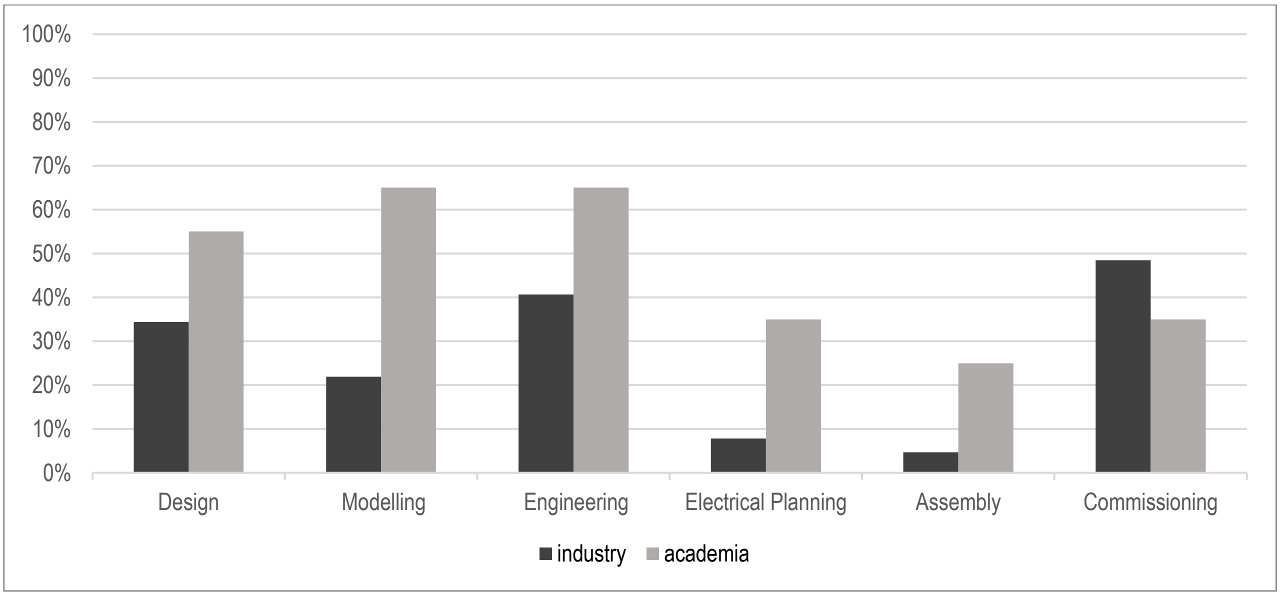


*Fig. 7. Virtual commissioning through the development process*


ISSN: 0012-7361 eISSN: 1989-1490 / DYNA Vol.96 nº6 DOI: https://doi.org/10.6036/10244

The results in Fig. 7 show that virtual commissioning is still mainly performed during the commissioning stage in industry as opposed to previous development stages. However, academia agrees with the statement defined in RQ1.4, in which virtual commissioning is carried out at earlier stages such as design, modelling and engineering. This discloses a discrepancy between academia and industry in terms of the practice of virtual commissioning during the development process.

## 3.5.- RQ1.5-RQ1.6 RESULTS

The following table addressed RQ1.5 and RQ1.6 by identifying and summarizing the main benefits and challenges identified in the industry and academia with respect to virtual commissioning.

| **Benefits** | **Challenges** |
|---|---|
| • Testing without disrupting the physical system<br>• Higher test coverage<br>• Ability to reconfigure in virtual, test and validate the system before physical commissioning<br>• Reduce time to market, errors and costs<br>• Better root cause analysis in case of failures<br>• Calmness and security perception during FAT and SAT.<br>• Final product quality improvement | • Standardisation and interoperability<br>• Software functionality limitations<br>• Systems variability<br>• Validity and fidelity of simulation models<br>• ROI: efforts vs benefits<br>• Traditional mindsets<br>• Scope limited to PLC testing<br>• Lack of required simulation fidelity details.<br>• |

## 3.6.- RQ2.1 RESULTS

There exists a wide range of definitions of the digital twin and its concept has been evolving over the years. Hence, RQ2.1 address this issue by identifying and defining the key aspects and components of a digital twin according to the industry and academia. Surveyed participants were asked to select the closes definition of a digital twin as depicted in the X axis of Fig. 8.

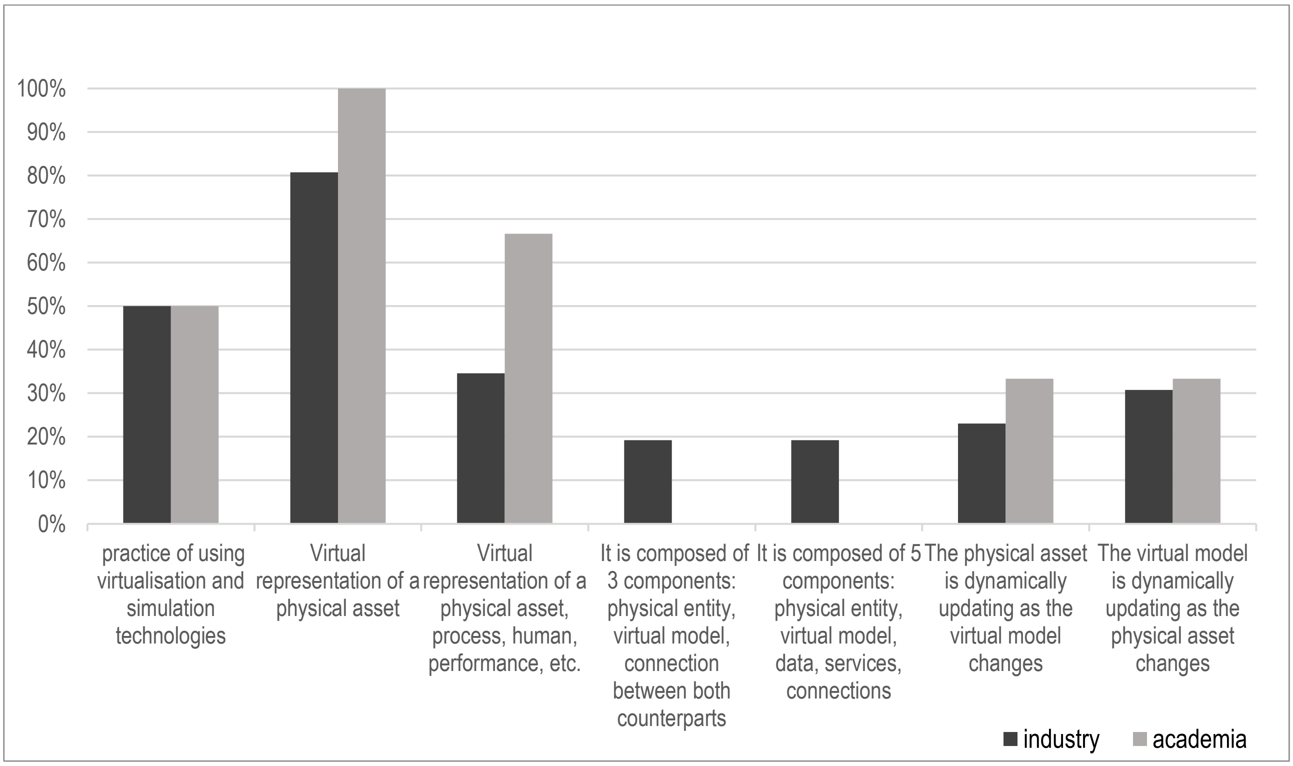


*Fig. 8. Digital twin definition*


ISSN: 0012-7361 eISSN: 1989-1490 / DYNA Vol.96 nº6 DOI: https://doi.org/10.6036/10244

According to the results, the digital twin is defined mainly as the virtual representaion of a physical asset by both academia and the industry, in which 67% of researchers think that it could also represent a process, human, performance, etc. Interestingly, only a 50% of the industry and academia defines it as the practice of using virtualisation as simulation technologies.

## 3.7.- RQ2.2 RESULTS

RQ2.2 measures the industrial readiness in terms of the implementation of the digital twin. In this matter, participants were asked to indicate the degree of implementation with a number between 0 (not been implemented yet) and 10 (fully implemented). Results are shown in Fig. 9, in which the implementation degree is classified as low (1-3), medium (4-6) or high (7-10).

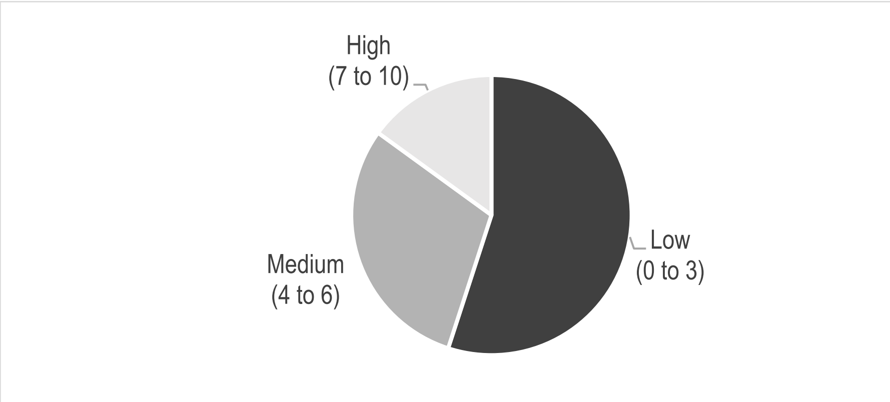


*Fig. 9. Degree of implementation of the digital twin in industry*

According to Fig. 9, a 55% of industry practitioners have not yet implemented the digital twin or its implementation is low. The results show that 30% of the industry have partially implemented the digital twin, and %15 have developed it with a high degree of implementation level. In overall, the implementation of the digital twin is still in progress.

## 3.8.- RQ2.3-RQ2.4 RESULTS

The survey identified the main benefits and challenges of the implementation of the digital twin in response to RQ1.3 and RQ1.4, and are set out in the table below:

| Benefits | Challenges |
|---|---|
| • Process optimisation<br>• Real time monitoring<br>• Virtual commissioning enhancement<br>• Reduction of costs and time<br>• Quality improvement<br>• Remaining useful life (RUL) computation<br>• Viability analysis | • Lack of data to train the simulation model (not enough data)<br>• Model calibration and synchronisation<br>• Data model adjustment: only necessary at required level<br>• Standardisation of interfaces and interoperability<br>• ROI: efforts vs benefit |

## 3.9.- RQ3.1 RESULTS

Virtual commissioning verifies and validates the system before deploying it to operations. As discussed in RQ2.1, it performs a series of verification tasks. These verification tasks could cover a wide set of tests such as mechanical verification, validation of the PLC, validation of the CNC configuration, CNC part program validation, controller hardware verification, electrical system verification, among others.


ISSN: 0012-7361 eISSN: 1989-1490 / DYNA Vol.96 nº6 DOI: https://doi.org/10.6036/10244

RQ3.1 identifies the verification and validation tasks that are carried out during virtual commissioning by industrial practitioners and academia, as depicted in Fig. 10. Results show that tests are carried out mainly for mechanical verification in industry (88% of industry practitioners), although a 69% percent of the industry also performs virtual commissioning for validating the PLC, CNC configuration and CNC part program. Moreover, a 44% of industry tests the controller hardware, and a 31% verifies the electrical system. Results are similar in academia with a slightly lower percentage. This clearly demonstrates the importance of validation and verification in all engineering disciplines.

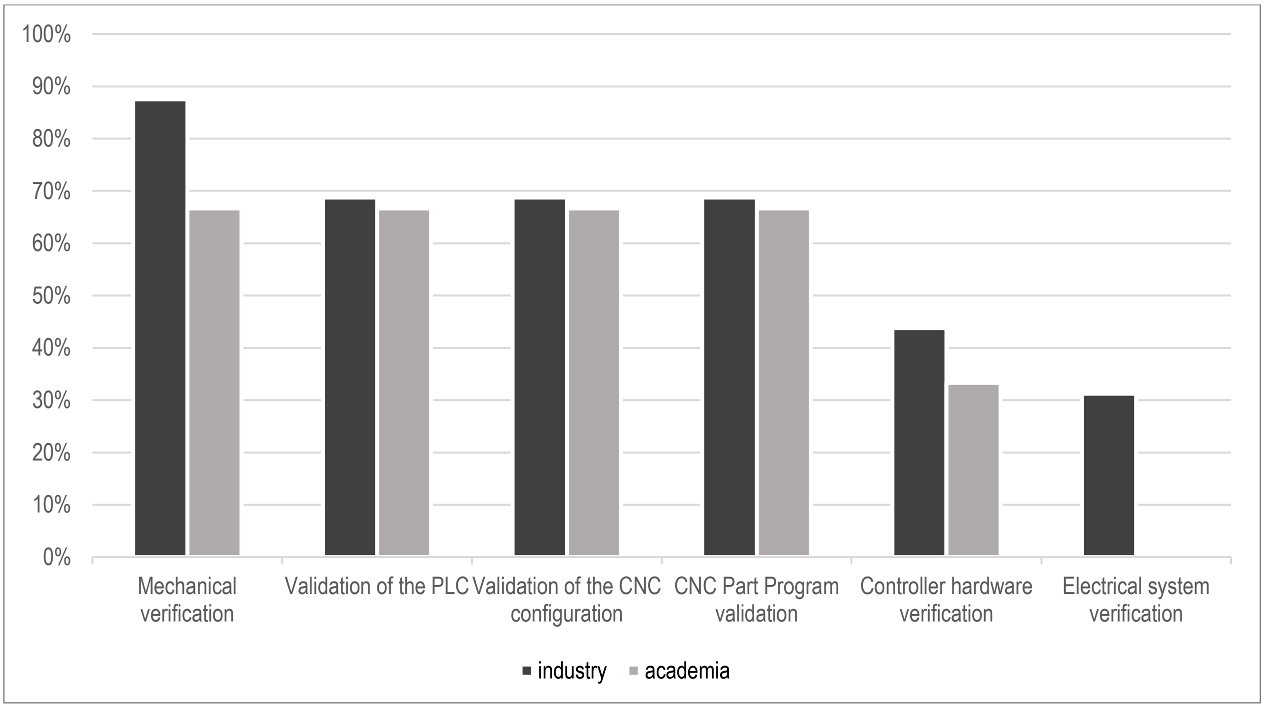


*Fig. 10. Validation and verification tests*

## 3.10.- RQ3.2 RESULTS

In terms of testing procedures, RQ3.2 aims at identifying the current industrial testing practices for virtual commissioning. These tests could be fully automated or performed manually. Thus, industrial practitioners where asked whether tests were performed manually, with the help of a software (semi-automated) or automated, as seen in Fig. 11.

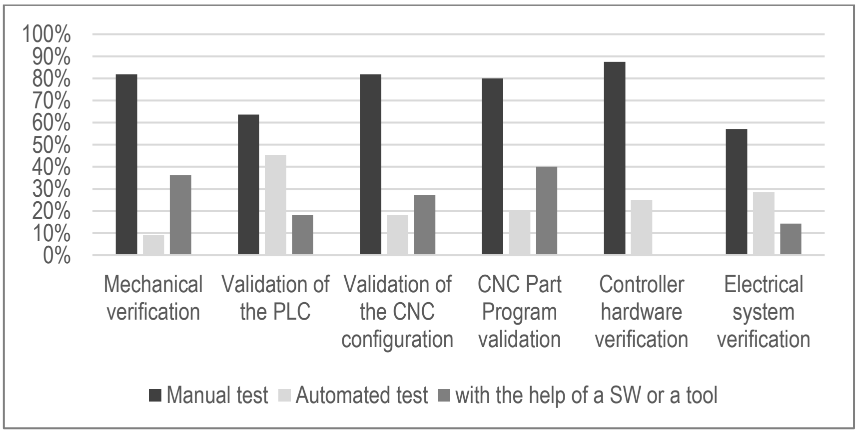


*Fig. 11. Testing procedure*


ISSN: 0012-7361 eISSN: 1989-1490 / DYNA Vol.96 nº6 DOI: https://doi.org/10.6036/10244

In overall, tests are carried out manually in industry, i.e. mechanical verification (82%), validation of the PLC (64%), validation of the CNC configuration (82%), CNC part program validation (80%), controller hardware verification (88%) and electrical system verification (57%). PLC Validation is the field that is most automated nowadays, although only a 45% of industrial practitioners performs automated virtual commissioning for the PLC. For the rest of the testing fields, automation is quite low, in which fewer than 29% of industry performs automated testing. In the case of semi-automated tests, CNC part program validation is the field that is most semi-automated in industry (40%). This shows a clear gap for automation.

## 3.11.- RQ3.3 RESULTS

Following RQ3.2, RQ3.3 examines the need of automating the tests indicated in RQ3.1. Industry and academia practitioners had to answer if it was beneficial automating them. Thus, Fig. 12 shows the percentage of the surveyed industrial and academic population that were in favor of automating the mechanical verification, validation of the PLC, validation of the CNC configuration, CNC part program validation, controller hardware verification, and electrical system verification.

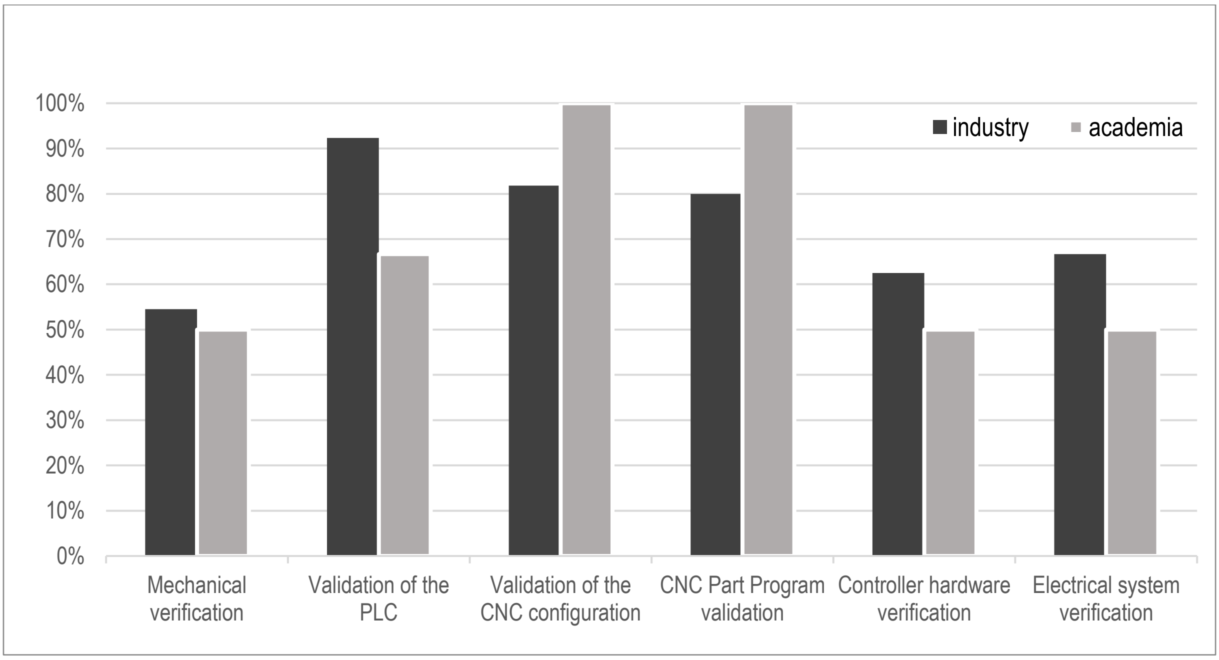


*Fig. 12. Automated tests – beneficial?*

According to the results, both academia and industry highlight the importance of automating tests for the validation of the CNC configuration, CNC part program validation and PLC validation. The former two are critical for academia (100% of the surveyed population agreed on the need of automating them), in which are also important for the 82% of the industry. A 92% of the surveyed industry practitioners think that it is highly beneficial automating the validation of the PLC, in contrast to the 67% of academia. Moreover, a 67%, a 63% and 55% of the industry agrees on automating the verification of electrical system, the controller hardware verification, and the verification of the mechanical system, respectively.

In overall, the presented results show a real need for enhancing the testing procedures of virtual commissioning by automating the aforementioned validation and verification tasks.


ISSN: 0012-7361 eISSN: 1989-1490 / DYNA Vol.96 nº6 DOI: https://doi.org/10.6036/10244

## 3.12.- RQ3.4 RESULTS

Lastly, RQ3.4 addresses the challenges that industry is facing when performing the tests indicated in RQ3.1. Fig. 13 depicts the challenges that were surveyed on this matter, such as, problems related to the controller hardware and software, errors encountered on the simulator/emulator software, PLC related ones, errors on the mechatronic system, communication and integration problems, issues related to the execution time, lack of precision and stability, unexpected circumstances, and issues from previous development stages.

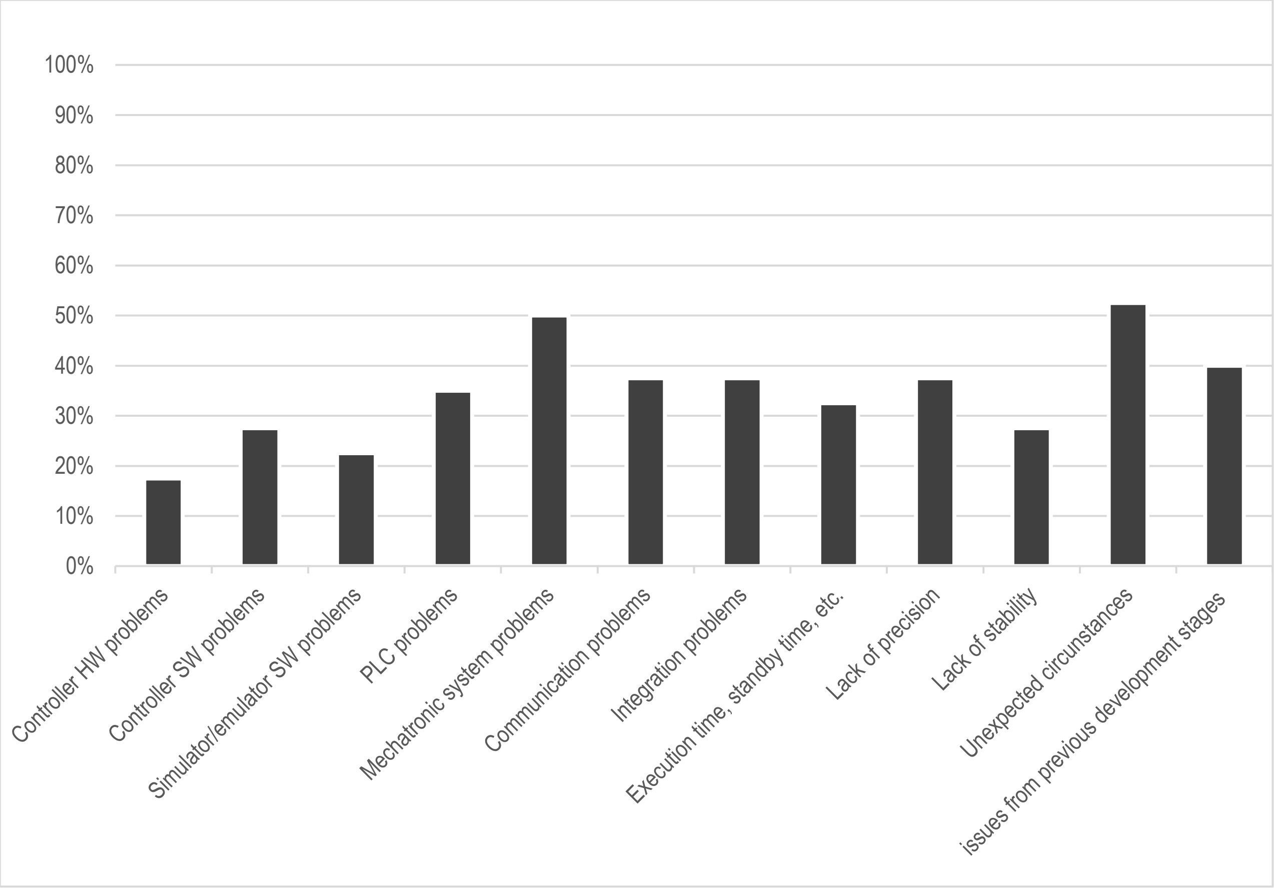


*Fig. 13. Testing challenges*

The results in Fig. 13 indicate that there is a great variety of challenges, in which unexpected circumstances and mechatronic system problems are the most common ones.

## 4. – THREATS TO VALIDITY

### 4.1.- INTERNAL VALIDITY

An internal validity thread is the sample size of the survey. However, we mitigated this by selecting a wide range of participants with different backgrounds (mechanics, electronics, automation, telecoms, computer science, ICTs, etc.) and years of experience in industry and academia.

Another internal thread could be related to the difficulty in understanding the questions. We mitigated this by contextualizing the topic with basic definitions in the beginning of the survey. Moreover, survey participants could freely comment on open questions about specific topics.


ISSN: 0012-7361 eISSN: 1989-1490 / DYNA Vol.96 nº6 DOI: https://doi.org/10.6036/10244

## 4.2 - EXTERNAL VALIDITY

An external thread could be the demographical area of the samples. This is mainly limited to the companies involved in the survey, which might be biased to the Basque Country region, northern Spain. Hence, we could not generalize the results. Instead, we think that it could represent well enough the machine tool sector of that area, which turns to be one of the leading areas in Spain.

## 5. - CONCLUSION

This paper presents an industrial empirical survey about virtual commissioning in the machine tool sector. The survey was mainly carried out within the machine tool sector and research centers in the region of the Basque Country, northern Spain.

The survey attempts to benchmark the industry against academia to bring awareness of the existing industrial needs and challenges in terms of virtual commissioning practices. Hence, three set of research questions were surveyed to address virtual commissioning related practices, the technological readiness of the digital twin for virtual commissioning, and testing procedures and practices when commissioning. The results show that in overall, industry is behind academia:

- The survey shows a clear need for virtual commissioning to shorten time to market and errors during commissioning. However, there is still little awareness of the full benefits of virtual commissioning in industry. Academia highlights the capability to perform a series of collaborative verification tasks between different engineering disciplines through the whole development process, whereas only a low percentage of the industry is aware of it. The results show that industry still performs virtual commissioning mainly in the last stage of the development process. Hence, virtual commissioning should be carried out during the whole development process (design, engineering, commissioning) to shorten time to market, errors and hence, costs.
- The industry is facing challenges in regard to virtual commissioning. Among others, standardisation and interoperability, software limitations, return on investment (ROI), and simulations fidelity were highlighted. Moreover, traditional mindset in industry was also raised as an issue to invest in such technologies.
- While the digital twin is foreseen as a promising simulation technology for virtual commissioning, its implementation is still low in industry. According to the results, the industry is still reluctant to invest in such technologies in terms of ROI due to the required efforts. In this matter, the industry is facing with standardisation problems when implementing such technologies. Lack of available data and model adjustment seem to be also major challenges in industry.
- Most of the testing practices carried out during virtual commissioning are still performed manually in industry, which shows a clear need for automation. Moreover, the surveyed industry practitioners indicated an emergent need for enhancing the testing procedures by automating them. Thus, in the near future, verification and validation should get automated to speed up with virtual commissioning practices and reduce time to market.

In conclusion, while digital twin based virtual commissioning literature is developing quickly, its practical implementation is not yet appropriately addressed. Thus, existing testing challenges need to be resolved in industry. Testing procedures should be therefore enhanced, and similarly the identified gaps should be fixed in the future in order to close the gap between academia and industry.

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ISSN: 0012-7361 eISSN: 1989-1490 / DYNA Vol.96 nº6 DOI: https://doi.org/10.6036/10244