engineering proceedings

Proceeding Paper

Synergies Between Virtual Commissioning and Digital Twins †

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† Presented at the 2024 IEEE 7th International Conference on Knowledge Innovation and Invention, Nagoya, Japan, 16–18 August 2024.

Abstract: Virtual commissioning (VC) and digital twins (DTs) are two key enabling technologies of Industry 4.0 (I4.0), which can enhance operational efficiency, optimize resource utilization, streamline the development and deployment of automation systems, and accelerate innovation in manufacturing and industrial processes. However, studies examining the synergy between these two technologies are still lacking. To address this research gap, this study aims to investigate the technological relationships and synergies between VC and DTs in the context of I4.0. The results suggest a strong relationship between VC and DTs since they share similar technological components, such as the digital model. Moreover, the result indicates that the concurrent use of VC and DTs can help leverage both technologies and their added value by increasing model reusability. Different strategies are proposed for combining VC and DT functionalities, highlighting how VC can support DTs, how DTs can support VC, and how both technologies can be integrated. It also provides future research directions.

Keywords: industry 4.0; virtual commissioning; digital twins; digital model; simulation

Academic Editors: Teen-Hang Meen, Chun-Yen Chang and Cheng-Fu Yang

Published: 24 February 2025

Citation: Tanegue, H.B.D.; de Paula Ferreira, W.; de Assis, R.F.; Brodeur, D. Synergies Between Virtual Commissioning and Digital Twins. *Eng. Proc.* **2025**, *89*, 12. https://doi.org/10.3390/engproc2025089012

1. Introduction

Virtual commissioning (VC) and digital twins (DTs) are two primary simulation-based technologies adopted in the context of Industry 4.0 (I4.0) [1–4]. VC facilitates virtual testing and systems validation before physical commissioning, reducing integration problems and saving time for optimization or early delivery [5]. DTs involve creating digital counterparts of a physical system, which can simulate, monitor, and optimize system performance [6]. The synergistic application of VC and DTs facilitates the application of both technologies and increases the accuracy and reusability of digital models [7]. This integration is increasingly recognized as transformative, attracting increased interest from academia and industry alike [8].

VC is mainly used in designing and developing automation control systems to facilitate the testing, verification, and validation of programmable logic controller (PLC) codes and systems integration. This approach enhances system reliability from the earliest stages of development [9]. VC methods for production systems include virtual commissioning Software-in-the-Loop (SIL) and Hardware-in-the-Loop (HIL) [10]. SIL establishes a fully virtualized test environment by integrating a virtual plant with a virtual controller to enhance design accuracy and operational readiness. On the other hand, HIL involves a real controller, enabling real-time testing of the controller's physical components within a simulated operational context.

Integrated into the DT framework, these VC techniques can complement and enhance the accuracy of design simulations and the operational efficiency of systems.

DTs are mainly used for product and asset life cycle management. It is based on three essential components: physical models in the real world, virtual models in a digital environment, and data connections that facilitate interactions between the two [11]. Furthermore, in exploring DT-related concepts, Kritzinger et al. [12] emphasize the importance of understanding the distinction between three key terms: "digital model", "digital shadow", and "digital twins". The digital model refers to a simplified representation of a physical object, often static and without continuous interaction with its physical counterpart. The digital shadow is more dynamic, so it reflects changes in the physical object in real time but with limited interaction. Finally, DTs represent the most advanced integration, with a digital replica constantly interacting (in real or near real-time) with its physical counterpart.

Although considerable research has been carried out on the individual applications of VC and DTs in the context of I4.0, more research is needed on their use in an integrated way. The combined architecture of VC and DTs represents an advanced integrated approach in I4.0 [10–12]. Studies generally focus on optimizing the stand-alone capabilities of VC and DTs, such as improving system testing through VC or enhancing life cycle management with DTs [13,14]. However, these works do not explore the possible synergies that arise from a cohesive application of both technologies. The intersection of VC and DTs where virtual testing and real-time system monitoring could theoretically converge thus remains to be explored.

This study aims to fill this gap by investigating how VC can complement DTs and vice versa, through a systematic review of studies implementing VC and DTs. The review identifies key statistics and trends that illustrate the current status and impact of such integrations using bibliometric and content analysis. The analysis also focuses on the methodologies and spin-offs to find out (1) how VC supports the development of DTs, (2) how DTs support the development and effectiveness of VC, and (3) the consequences of their mutual option or integration.

The remainder of this article is organized as follows. Section 2 introduces the methodology. Section 3 presents the results, followed by a discussion in Section 4. Section 5 presents avenues for future research. Lastly, Section 6 concludes this study.

2. Methodology

We adopted the preferred reporting items for systematic review and meta-analyses (PRISMA) methodology [15,16]. Its flowchart details the process during the various stages of the review (identification, eligibility assessment, and inclusion) and its checklist provides guidelines on the elements. In total, 136 articles were initially retrieved using the research protocol in Table 1. After screening, 75 records were discarded since they were outside the scope of this research—not exploring both VC and DTs narrowed down the scope to 61 studies. Six articles were excluded because DTs and VC were only used as keywords or quoted expressions. The remaining 55 articles were then prepared for in-depth review.

Table 1. Search Protocol.

Data source:	Scopus
Search string:	"Virtual commissioning" AND "Digital twin"
Period:	From 2011 (emergence of the term Industry 4.0) to 31 January 2024
Search fields:	Title, abstract, and keywords
Language:	English
Document:	Journal and Conference articles

3. Results

3.1. Bibliometric Analysis

Figure 1 shows the distribution of publications over time. This result was used to infer a growing trend in the scientific literature on the adoption or integration of VC and DTs.

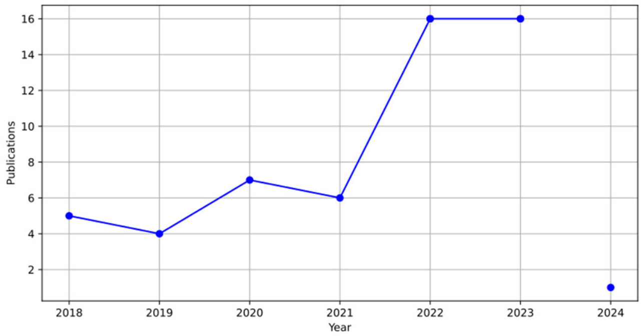

Figure 1. Number of publications per year.

We analyzed 55 articles, 38 of which were published in 26 conferences, highlighting various forums. Among these, publications in the Procedia Conference series—including Procedia CIRP and Procedia Manufacturing—totaled 11 articles, corresponding to 29%. IEEE conferences, such as the "IEEE International Conference on Emerging Technologies" and "Factory Automation", and the "IEEE International Symposium on Industrial Electronics", contributed 9 articles (23%). The remaining 18 articles (48%) were distributed among various other conferences. The review included 17 articles (31%) published in peer-reviewed journals. The journal "Machines" stands out with three articles (5.45%). Other journals, such as "Sensors", "IEEE Access" and the "International Journal of Computer Integrated Manufacturing" contributed one article, reflecting the diversity of academic forums dealing with VC and DTs.

Figure 2 illustrates the distribution of the most frequent terms taken from the publications' titles, abstracts, and keywords, using VOSviewer to visualize word density. This representation reveals three main clusters, focusing on key themes: VC, DTs, and production system.

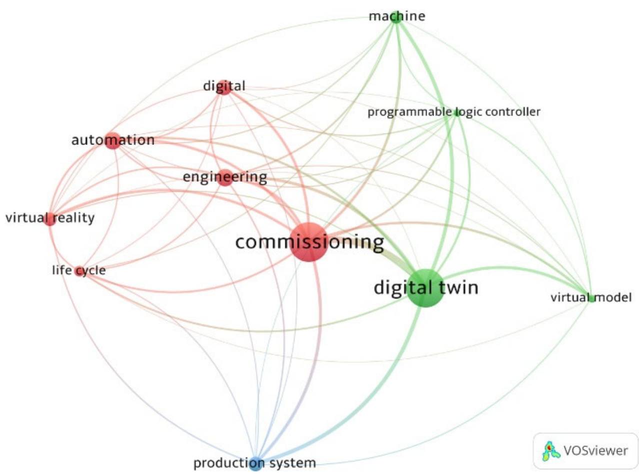

Figure 2. Keywords network visualization. The green nodes represent the *Digital Twins* cluster, the red nodes represent the *Virtual Commissioning* cluster, and the blue nodes represent the *Production Systems* cluster.

Figure 3 shows the geographical distribution by institutional affiliation of authors. Germany leads with 70 affiliations, followed by China and Spain with 29 and 19 affiliations, respectively. Belgium and Sweden also stand out with 16 and 14 affiliations, while the United Kingdom and Russia have 13 authors each. The United States and Italy have eight authors each, and Finland and Mexico have six authors. Japan and France have one and five authors.

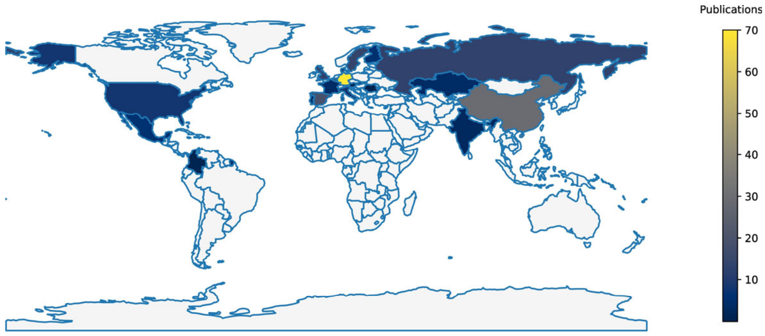

Figure 3. Geographical distribution by affiliation of authors.

Most of the research on VC combined with DTs is carried out in Europe, with Germany having the highest author contributions (Figure 3). The number of authors from China and Spain indicates a growing interest in the research area. The diversity of affiliations/countries suggests a global recognition of the importance of these technologies. Figure 4 represents a collaboration matrix of the authors' affiliations to understand frequent interactions and prominent scientific collaborations. The publications by Germany, China, and Belgium highlight national research networks. The heatmap suggests that future initiatives foster diverse collaborations, particularly between countries with significant individual contributions but less involved in collaborative efforts.

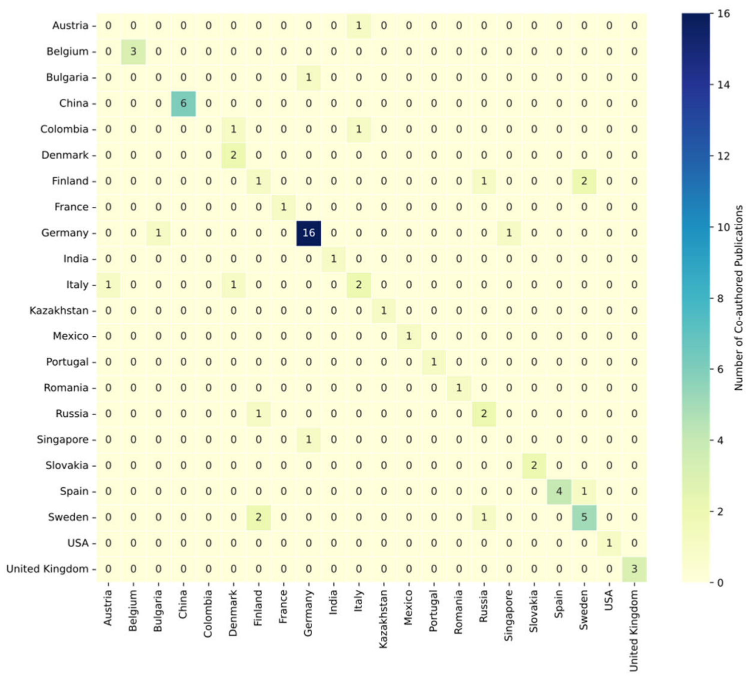

Figure 4. Collaboration. The color intensity represents the number of co-authored publications between countries, with darker shades indicating stronger collaboration.

VC allows a manufacturing system to be verified by performing an emulation involving a virtual factory and a controller or a virtual factory with a simulated controller [17]. Figure 5 shows the predominance of the SIL method with 51% of the publications. This is followed by HIL and the combination of SIL and HIL with 18% and 16%, respectively.

Figure 5 shows a preference for SIL due to its flexibility for detailed simulation without specific hardware. Despite offering a more comprehensive and integrated simulation, the combined use of SIL and HIL appears in lower proportion, suggesting limitations such as complexity and higher costs.

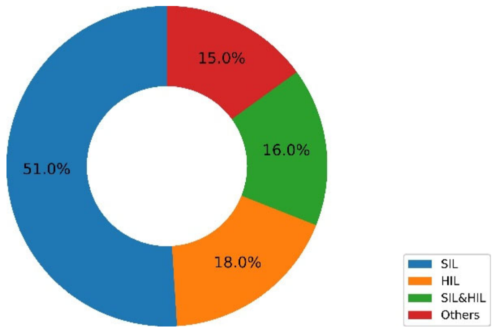

Figure 5. Virtual commissioning methods.

In total, 42% adopt the open platform communications unified architecture (OPC UA) protocol which has interoperability and security and is essential for efficient systems integration in industrial environments. The TCP/IP and PROFINET protocols are less frequent with 5 and 2%, respectively. Interestingly, 49% of the publications do not specify the communication protocol. Furthermore, 18 dealt with "Hypothetical Problems", while 17 addressed "Real Problems", indicating an almost equal split between theoretical investigations and applications. Finally, 17 articles were categorized as "Conceptual Studies". Three publications are "Literature Reviews", with different scopes from this research.

3.2. Content Analysis

To better grasp the concepts of VC and DTs, an in-depth comparative analysis of these technologies was carried out, highlighting their main similarities and differences (Table 2).

Table 2. Differences and Similarities of VC and DTs.

Features	VC	DTs
Purpose	Simulate and test systems before commissioning for factory acceptance tests.	Create and maintain an up-to-date digital replica of the real system.
Life cycle	Used at specific points in the plant life cycles.	It can be used throughout the product and plant life cycles.
System	Does not require an existing system.	Requires an existing system with connected devices.
Data types	Use hypothetical or simulated data.	Use real and historical data for simulation and analysis.
Optimization	Offline	Both offline and online
Technologies	Simulation models, PLCs, and communication protocols.	Mainly simulation models, sensors, actuators, smart devices, communication protocols and data service.

The link between VC and DTs reveals its potential and attracts increasing attention in research from academia and industry alike [18]. It is essential to create an environment where these applications are optimally explored [19]. This integrated approach has growing interest, encouraging further research. As illustrated in Figure 6, three strategies combining VC and DT technologies were identified.

- VC supports DTs: VC refines DTs using high-precision simulations to model realistic behavior, thus strengthening life cycle management and facilitating continuous improvement. The simulation models developed for VC are reused to facilitate DT development.
- DTs support VC: This strategy uses DTs to improve VC by verifying designs and validating control configurations before deployment, simplifying testing, and enhancing reliability.
- Integration of VC and DTs: This strategy harnesses the symbiotic relationship between VC and DTs to maximize the benefits of each technology. It ensures real-time synchronization with operational data, increasing their effectiveness from the initial design phases. One of the main approaches is to make VC a subcomponent of DTs, whose scope of application is vast and extends across the entire product and plant life cycles [20].

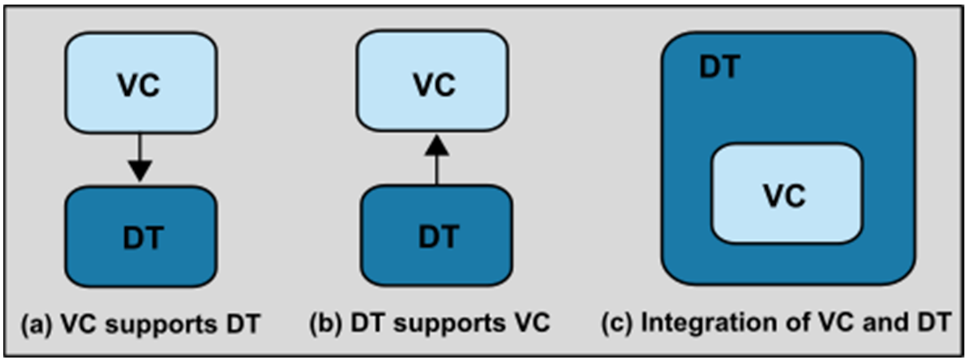

Figure 6. Taxonomy of approaches of combining VC and DTs.

Table 3 shows the examples of applications of these three approaches to combining VC with DTs. DTs reinforce VC by verifying initial designs, testing, and validating new PLC and HMI controls. At the same time, VC contributes to DT development by enabling accurate simulations and immersive experiences. The techniques used for this integration vary, from combining mechanical and electrical systems to create DTs to using advanced platforms such as Matlab Simulink and CoDeSys to simulate the behavior of complex systems. In addition, VC models are used to support and improve the efficiency of DTs, since designing DTs involves creating a virtual prototype connected to a system simulator and an industrial controller [21]. As an example, Khan et al. [22] introduce a model analysis-based platform that offers manufacturing companies an initial means of integrating a VC model that functions as a DT. These approaches demonstrate how VC and DT models are used strategically to improve the design and functionality of industrial systems.

Table 3. Examples of Approaches Combining VC and DTs.

Class	Approach	Ref.
VC supports DT	Use CoDeSys Win Control V3 and OPC with Experior to test and validate the DT designed in Matlab, facilitating optimization, simulation, and debugging in a virtual environment integrated into manufacturing systems.	[23]
	Use Automation Studio for its precision in closed-loop simulation and testing (HIL, SIL), to develop a DT with Unity, benefiting from an immersive experience and improving the interaction between the DT and its real-life counterpart.	[24]
	Integrate CoDeSys for PLC logic and OPC UA for signal exchange between Simulink and Webots, ensuring precise information processing and instant visual feedback, while developing a modular VC architecture to prepare a DT.	[25]
	Proposes a three-phase methodology for the DT: digital simulation of real-world behavior, communication via PLC code between the real and virtual worlds (VC), and integration of the simulation with real-world automation, followed by the complete implementation of the DT of a production line.	[26]
DT supports VC	Use a DT developed with Simumatik3D to facilitate reverse engineering via VC to verify initial designs and test new PLC and HMI controls, reducing cost and time to actual commissioning.	[27]
	Combine mechanical and electrical systems to create a DT, to which control logic is applied via a virtual debugging interface, solving the problems of long development cycles, high costs, and incompatibility between research and development.	[28]
	Combines semantically DT, industrial controller, and SCADA via OPC UA to describe an efficient VC method for the paint industry.	[29]
Integration of VC and DT	Proposes a progression methodology from VC simulation to DT and vice versa, establishing a seamless bidirectional process flow between software and virtual/real interaction for machine development in a dynamic industrial context.	[30]
	Integrates discrete-event simulation and agent-based modeling to connect DT Emulation (DTE) with a PLC, boosting the efficiency and reliability of modular production systems.	[31]
	Examines recent methods for developing VC-enhanced DT and the use of DT-optimized VC models, enabling accurate simulation during both design and operation.	[32]

4. Discussion

The results of the study highlight the predominant use of SIL VC methodologies and their flexibility and capacity to conduct detailed simulations in the absence of specific hardware requirements. Nonetheless, the sparse application of hybrid SIL and HIL approaches indicates challenges such as increased complexity and elevated costs. The results also emphasize the distinct but complementary roles of VC and DTs. While VC is predominantly used in pre-operational phases to simulate and test systems for validation purposes, DTs extend their usefulness throughout the system's operational life cycle, continuously interacting with and adapting to the real system. This delimitation encompasses the scope and application of VC and DTs in industrial practice, as it reflects the need for technologies that can accurately initialize systems and dynamically adapt over time.

VC can support DT development by offering high-fidelity simulations that accurately reflect real-world behavior. These simulations based mainly on SIL methods allow detailed modeling without specific hardware to reduce costs and increase the flexibility of the development process. As highlighted by Lechler et al. [20], VC simulation models serve as the basis for the development of DT models. Also, DTs can support VC by improving the accuracy of post-commissioning simulations and responding adaptively in real time to production challenges. The combination of DTs with VC allows the accurate verification of designs and the validation of control configurations before deployment and continuous improvement after commissioning [33,34].

The integration of VC and DTs allows for optimizing the development and management of industrial systems [20]. This integration is manifested through a progression methodology that enables a seamless two-way process flow, connecting simulation paradigms to bring the virtual and physical spheres together. In addition, this collaboration facilitates better anticipation and management of potential problems, both before and during production, as indicated by Shen et al. [35] and Wang et al. [36], highlighting the critical relevance of this integration for I4.0. By enabling real-time synchronization with operational data, the strengths of both technologies are used to optimize system design and functionality, from the initial phases to maintenance. Moreover, VC is used at particular points in the plant life cycle and depends heavily on simulation model availability, which requires significant effort to develop, preventing VC from being widely adopted in the industry due to its cost [37,38]. However, by integrating the adoption of VC with DTs which relies on simulation models, the use of VC is prolonged to prorate the development cost with DTs, making its adoption appealing to the industry. As highlighted in reference [37], simulation models developed for VC cannot be reused without major effort for DTs due to initial design choices. However, by considering the concurrent adoption of both technologies, engineers can develop simulation models in a way that they can be reused more easily.

5. Future Research

This study also reveals some directions for future research efforts (Figure 7). The use of VC and DT simulation models throughout the life cycle reveals a significant research opportunity in developing methodologies that transition between pre-operational VC simulations and continuous DT operational management [5]. These methodologies allow for the reuse of simulation models and real-time feedback from DT operations to refine VC simulations, optimize configuration, and make constant adjustments. Another gap exists in data management, where there is a need for hybrid models that integrate the hypothetical or design data of VC with the historical data of DTs. This integration increases the accuracy of simulations and the predictive capabilities of DTs. For this, real-time interaction/synchronization mechanisms also represent a challenge.

Other areas for future research are the automatic generation and reuse of simulation models, which represent an opportunity for sustainability and efficiency in VC and DT applications. Strategies for effective model reuse can significantly reduce resource consumption and accelerate the development process. This addresses the gap in current practices, where models are built from scratch for each new project, preventing the widespread adoption of VC and DTs. Lastly, education and training on VC and DTs must be conducted to prepare engineers to develop more complex automated systems in I4.0 and broaden the use of these technologies in industry.

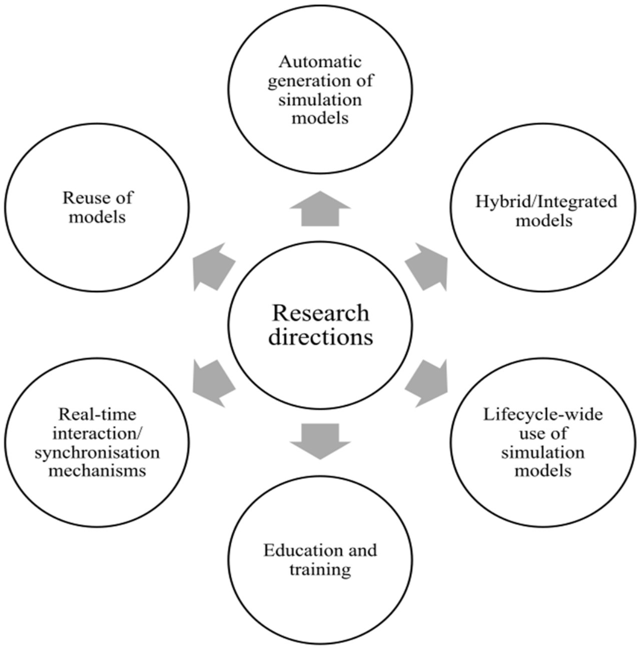

Figure 7. Main research directions.

6. Conclusions

We analyzed the synergies between VC and DT technologies in the context of I4.0 through a systematic literature review, enriching academic discourse on the subject. VC can support the development of DTs and vice versa, and the two technologies can be integrated with VC becoming a component of DTs. It highlights how these technologies significantly improve industrial system design, development, and improvement. By leveraging both VC's ability to perform detailed pre-operational testing and DTs' continuous monitoring and updating of system performance, substantial improvements in systems management can be achieved.

Combined VC and DTs improve simulation accuracy, facilitate its reuse, and enhance the life cycle management of industrial assets. This integrated approach promotes a more dynamic interaction between simulated models and real-world data, which contributes to the development of resilient and adaptable industrial systems. Specifically, the integration of VC and DTs facilitates real-time data flows that significantly improve decision-making processes and allow timely corrections and updates. These capabilities are key in today's fast-changing industrial environments, where the ability to respond quickly and accurately to operational fluctuations significantly affects overall efficiency and productivity.

Author Contributions: Conceptualization, H.B.D.T. and W.d.P.F.; methodology, H.B.D.T. and W.d.P.F.; validation, H.B.D.T., W.d.P.F., R.F.d.A. and D.B.; formal analysis, H.B.D.T.; investigation, H.B.D.T.; resources, W.d.P.F. and D.B.; data curation, H.B.D.T.; writing—original draft preparation, H.B.D.T.; writing—review and editing, H.B.D.T., W.d.P.F., R.F.d.A. and D.B.; visualization, H.B.D.T., W.d.P.F. and R.F.d.A.; supervision, W.d.P.F.; project administration, W.d.P.F.; funding acquisition, W.d.P.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) through the Alliance Grants program [grant number ALLRP 592520-23] and the Discovery Grant program [grant number RGPIN-2024-03880], as well as by Mitacs through the Mitacs Accelerate program in Canada.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data will be made available on request.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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