UNIVERSIDAD DISTRITAL
FRANCISCO JOSÉ DE CALDAS

Tecnura
https://revistas.udistrital.edu.co/index.php/Tecnura/issue/view/1327
DOI: https://doi.org/10.14483/22487638.24200

INVESTIGACIÓN

Petri Net Modeling of a Teleoperated Laboratory for Mechanical Ventilation Training

Modelado con Redes de Petri de un Laboratorio Teleoperado para entrenamiento en Ventilación Mecánica

Andrés Mauricio Valencia[1]

Fecha de Recepción: 12 de octubre de 2025 **Fecha de Aceptación**: 28 de abril de 2026

Cómo citar: A.M. Valencia, «Petri Net Modeling of a Teleoperated Laboratory for Mechanical Ventilation Training», *Tecnura*, vol. 30, n.° 88, jun. 2026. 19–37. https://doi.org/10.14483/22487638.24200

Abstract

Objective: To present the design of a digital learning ecosystem that integrates cyber-physical systems, remote platforms, and pedagogical strategies for mechanical ventilation training, using Colored Petri Nets as an emulation formalism.
Methodology: A model is proposed that articulates electromechanical components and computational applications with accessible virtual laboratories, employing Colored Petri Nets to formally represent the system's dynamic processes.
Results: The model provides an integrated architecture enabling remote training in mechanical ventilator operation, addressing the existing gap in healthcare professional education through virtual laboratories.
Conclusions: The developed ecosystem constitutes an innovative approach for mechanical respiratory assistance training, leveraging remote platforms and formal modeling to represent complex processes.

Keywords: Mechanical Ventilation, Virtual Learning Environments, Teleoperated Equipment, Cyber-Physical Systems, Colored Petri Nets, Simulation and Modeling, Remote Laboratories, Healthcare Professional Training

Resumen

Objetivo: Presentar el diseño de un ecosistema de aprendizaje digital que integra sistemas ciberfísicos, plataformas remotas y estrategias pedagógicas para la formación en ventilación mecánica, utilizando Redes de Petri Coloreadas como formalismo de emulación.
Metodología: Se propone un modelo que articula componentes electromecánicos y aplicaciones computacionales con laboratorios virtuales accesibles, empleando Redes de Petri Coloreadas para representar formalmente los procesos dinámicos del sistema.
Resultados: El modelo ofrece una arquitectura integrada que permite la formación remota en el manejo de ventiladores mecánicos, abordando la brecha existente en la capacitación de profesionales médicos mediante laboratorios virtuales.
Conclusiones: El ecosistema desarrollado constituye una aproximación innovadora para la formación en asistencia respiratoria mecánica, aprovechando plataformas remotas y modelización formal para representar procesos complejos.

---

[1] Docente de la Escuela de Ingeniería de sistemas y Ciencias de la Computación de la Universidad del Valle. Miembro del grupo de investigación BONOVO, GUIA. ROR Email: andres.valencia.restrepo@correounivalle.edu.co

Palabras Clave: Ventilación Mecánica, Entornos Virtuales de Aprendizaje, Equipos Teleoperados, Sistemas Ciberfísicos, Redes de Petri Coloreadas, Simulación y Modelado, Laboratorios Remotos, Formación de Profesionales de la salud.

Introduction

Ventilation, an innate physiological process critical for hemodynamic gas exchange (O_2 and CO_2), is typically performed autonomously [1]. Despite this, pulmonary disorders continue to constitute a predominant cause of global mortality and impairment [2]. This panorama has been aggravated by diverse factors, including pathological and ecological concerns [3], [4]. Specifically, the COVID-19 pandemic precipitated a considerable burden, manifesting as a clinical spectrum linked to SARS-CoV-2 infection. Its presentation spans from mild respiratory afflictions to severe interstitial pneumonitis and acute respiratory distress syndrome (ARDS) [5], thereby introducing novel complexities for clinical practitioners.

The escalation in fatalities and number of cases was propelled by multiple determinants. These encompassed a constrained inventory of apparatus for managing critically ill individuals, the hazard of pathogen transmission among clinical staff, cross-contamination originating from infected personnel, and logistical complications in the distribution of mechanical ventilatory support. On July 13, 2020, Bogotá, Colombia's capital, documented an intensive care unit (ICU) utilization rate of 97.3%, wherein 71.8% of occupied beds were allocated to COVID-19 patients during that period [3]. Concurrently, the city of Cali accounted for 1,780 fatalities out of a national total of 28,803 deaths associated with COVID-19 [4]. Consequently, mitigating the exposure of clinical staff to infected individuals is paramount for diminishing transmission risk, rendering the investigation of all viable methodologies an imperative objective.

Implementing digital transformation paradigms offers a pathway to diminish clinician exposure within both instructional and therapeutic contexts. Although numerous academic and commercial pulmonary simulators have been engineered [6]–[15], and the pandemic has accelerated the development of mechanical ventilators [16]–[28], a scarcity of information persists regarding cyber-physical structures that facilitate remote actuation. For instance, reference [29] proposed a taxonomy that categorizes ventilation initiatives across ten attributes, organized by constructs of manufacturability, flexibility, and expandability. As noted in [30], the engineering of such devices is directed by the confluence of sophisticated technologies, frequently characterized as "intelligent," although remote control and surveillance functionalities have been marginally addressed. Notwithstanding, [31] details a mechanical ventilator incorporating internet-based telemonitoring capacities, and [32] outlines a virtual simulation environment conceived as an autodidactic instrument for novice medical staff has been outlined [32]. While [33] conceded that further investigation is requisite before telemonitoring can be deemed a substantive enhancement in patient management, its application within clinical training milieus is endorsed.

Embracing a proactive stance, [34] introduced a foundational infrastructure intended to augment synergy among medical practitioners, technological suites, and digital informatics, thereby promoting the transition to cognizant domiciliary hospitalization. The uniformity and efficacy of integration and orchestration across disparate components and data streams, the adoption of stringent formal modeling methodologies—such as Colored Petri Nets (CPNs)—is recommended. As an example, [35] demonstrates how patient statuses and the correlations among clinical interventions and assets can be depicted inside a cloud-centric healthcare network utilizing CPN Tools. Correspondingly, [36] proposes a Petri net schema for a decentralized telemedicine system based on SOA and contemporary telecommunication protocols. In a cognate manner, [37] elaborates a mechanism enabling the remote oversight of rehabilitative protocols via teleoperated instrumentation. Furthermore, Colored Petri Nets were deployed in [38] to authenticate a decentralized configuration for locomotion assessment and in [39] to institute a security-oriented modeling architecture for digital learning infrastructures.

Within this conceptual milieu, the present investigation delineates an instructional platform that facilitates the actuation and monitoring of mechanical ventilation through digital emulation and online-enabled technologies. Owing to the event-driven dynamics intrinsic to the proposed system, its architecture is formally abstracted using a Colored Petri Net representation to meticulously encapsulate its operational logic.

Methodological Framework

This investigation was based on an adaptive methodological framework, conceptually grounded in the iterative cycles of the spiral development paradigm (Figure 1). The ensuing elaboration delineates the distinct phases constituting this research approach.

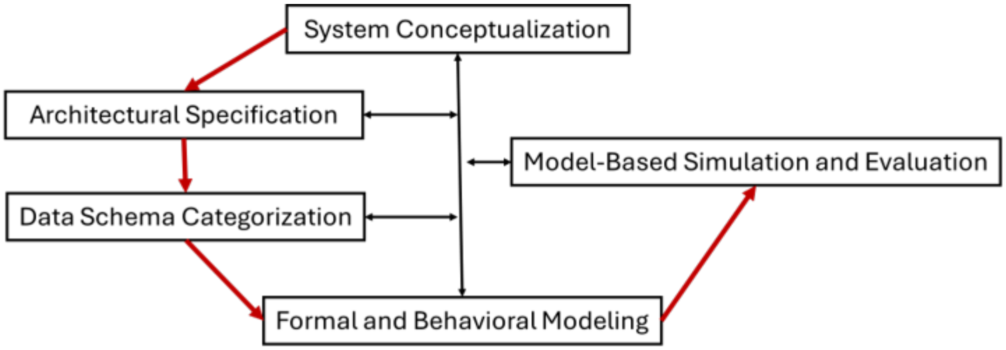

Figure 1. Methodological framework.

Source: own elaboration.

System Conceptualization:

The initial phase is dedicated to establishing a foundational understanding of the target system. This involves a meticulous analysis of its operational principles to identify core functions, primary architectural constituents, and contextual boundaries. The culmination of this stage yields a precise characterization of all system elements, facilitating a clear understanding of the synergies between physical and logical entities that enable the execution of designated processes.

Architectural Specification:

This stage focuses on formalizing the operational architecture of the system, leveraging the insights acquired from the preceding phase. The methodology advocates for the application of high-level structural schematics [40], which provide a holistic visualization of the system's topology and the interconnectivity between its central and peripheral components. The procedure initiates with the identification of principal system actors. Each entity is delineated by its fundamental purpose and its interaction protocols with other elements, maintaining a conceptual perspective devoid of implementation specifics. Completion of this phase yields a comprehensive layout blueprint of the system, highlighting key agents, auxiliary modules, and their functional interdependencies.

Data Schema Categorization:

Building upon the architectural schematics, an exhaustive inventory of critical system variables is compiled. The process begins by enumerating local variables, which are confined to separate functional units or modules. This is followed by the global variable specification, which facilitate data exchange across multiple operational segments. Performing this classification early in the development lifecycle is criticalbecause the resultant schema forms the basis for establishing data relationships in the final model, governing the information flow and transactional logic between system entities.

Formal and Behavioral Modeling:

In this phase, the system's operational specifications are refined through an evolved set of architectural diagrams. These representations are enriched with detailed descriptions of the dynamic behavior of the system, incorporating the data schema defined previously. The consolidation of this information guides the design of discrete functional modulesengineered to ensure robust performance of the simulated environment. The resulting diagrams are instrumental, as they supply the foundational input for constructing Colored Petri Net models, which validate the system's holistic functionality by defining its structural and dataflow properties.

Model-Based Simulation and Evaluation:

A suite of simulation scenarios is constructed by leveraging the outputs from all prior stages, each accompanied by specific observation criteria and performance indicatorsevaluation. Every scenario is architected in accordance with discrete analytical objectives, which may include evaluating resource utilization, verifying process concurrency, or appraising overall systemic throughputevaluation.

Results

Architectural Synopsis of the Remote Mechanical Ventilation Training Platform

The implemented cyber-physical framework for remote mechanical ventilation instruction was engineered to deliver experiential skill development via teleoperated interfaces (Figure 2). This solution is particularly advantageous for healthcare professionals and trainees facing geographical or infrastructural constraints that hinder access to conventional hands-on training. The platform's architecture is structured to cultivate the core competencies necessary for the adept clinical management of mechanical ventilation systems.

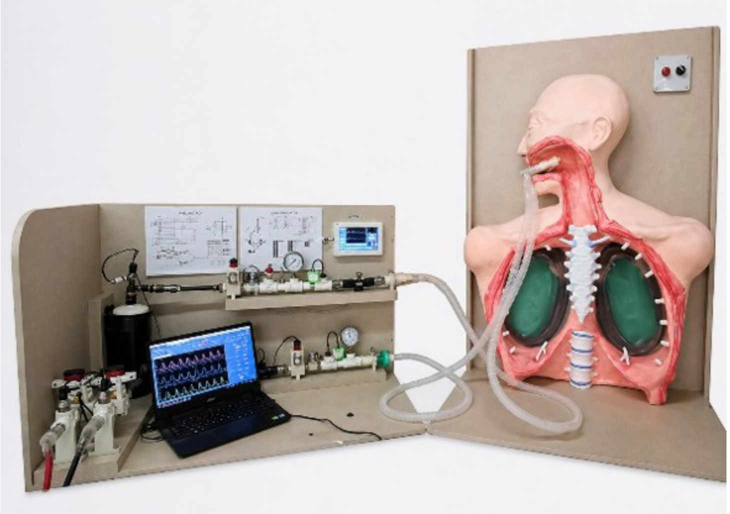

Figure 2. Mechanical Ventilator (MV) and Patient Emulator (PE)

Source: own elaboration.

A dedicated mechanical ventilation training laboratory was engineered to fulfill this objective, comprising two fundamental units: a ventilator simulator and a computational patient model. These entities are unified within a teleoperation infrastructure, permitting comprehensive command and monitoring via distinct human-machine interfaces (HMIs)—one allocated for the instructor and another for the student cohort. This split access model delineates user privileges and streamlines asset allocation, positioning the instructor as the system administrator with the authority to define and modulate the operational permissions granted to learners.

Trainees interact with the platform through their assigned interfaces, connecting via personal computing equipment. Initially, participants are assigned a read-only mode that is elevated to an active control state upon receiving explicit authorization from the instructor. This transition enables real-time adjustment of ventilator operational parameters from the student terminal.

Furthermore, the cyber-physical system incorporates a comprehensive data logging mechanismthat archives all operational information produced during instructional sessions within a centralized repository. This capability supports post-session auditing and analytical review, while also permitting the detailed tracing of user performance, documenting both appropriate and incorrect interventions. The databank captures three primary data classifications:

- **Control Parameters**: Configurable settings modified by the trainee to govern the operational modes of the ventilator simulator and the physiological patient model.
- **Clinical Contextualization Data**: The instructor supplied supplementary information to frame the patient emulator's state within a plausible medical narrative. While this data does not directly influence the emulator's dynamics, it serves to heighten the simulation's fidelity.
- **Apparatus Telemetry Data**: Live sensor readings—encompassing pressure, volumetric flow, and oxygen concentration—alongside the status of actuation components (e.g., Vacuum pumps, proportional solenoids, and binary actuators) integrated into the physical laboratory apparatus.

Functional Architecture of the Remote Ventilator Training Platform

The implemented communication structure facilitates synchronous interaction between a single instructor and multiple trainees, all interfaced concurrently with the ventilator simulator and the patient model. The system's functional topology, illustrated in Figure 3, delineates the principal data pathways and the interconnectivity between its constituent modules.

Core architectural constituents:

- **Instructor Command Console (Figure 4)**: This interface provides a supervisory control environment, facilitating direct instructor-student communication and full command over the physical apparatus—namely, the mechanical ventilator and patient emulator. It delivers exhaustive telemetry on equipment status and enables the dynamic allocation or revocation of trainee operational privileges.
- **Trainee Operational Terminal (Figure 5):** A digital simulation environment that facilitates mediated interaction with the ventilator system. All operational commands issued by the trainee are routed through and require validation by the instructor’s console, ensuring supervised execution.

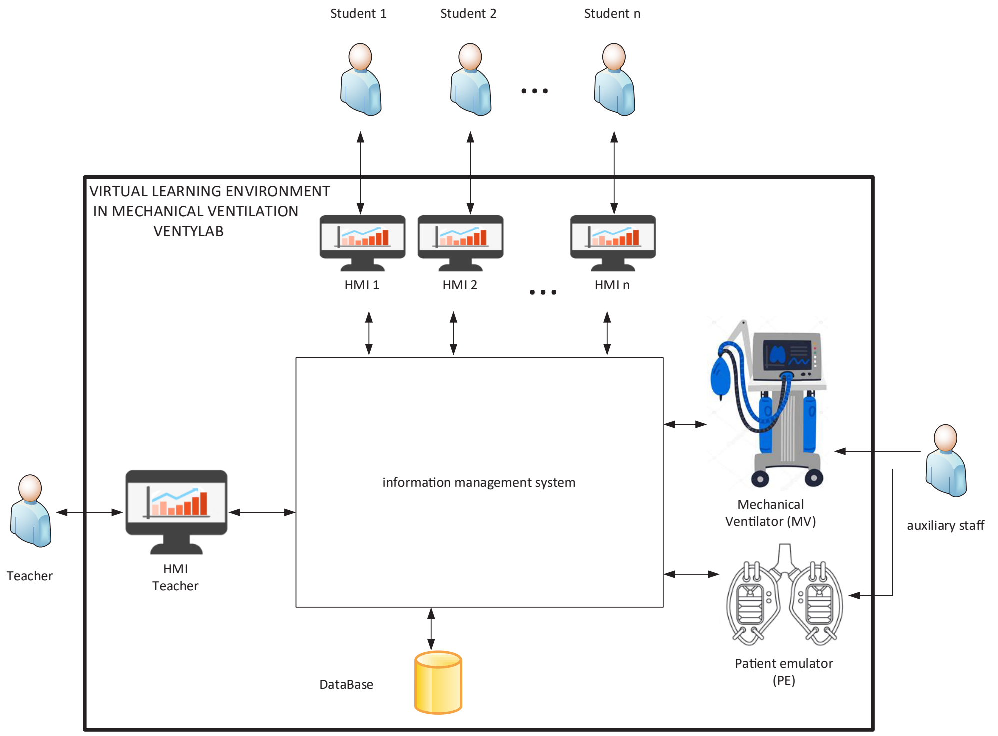

Figure 3. Characters involved in the information system.

Source: own elaboration

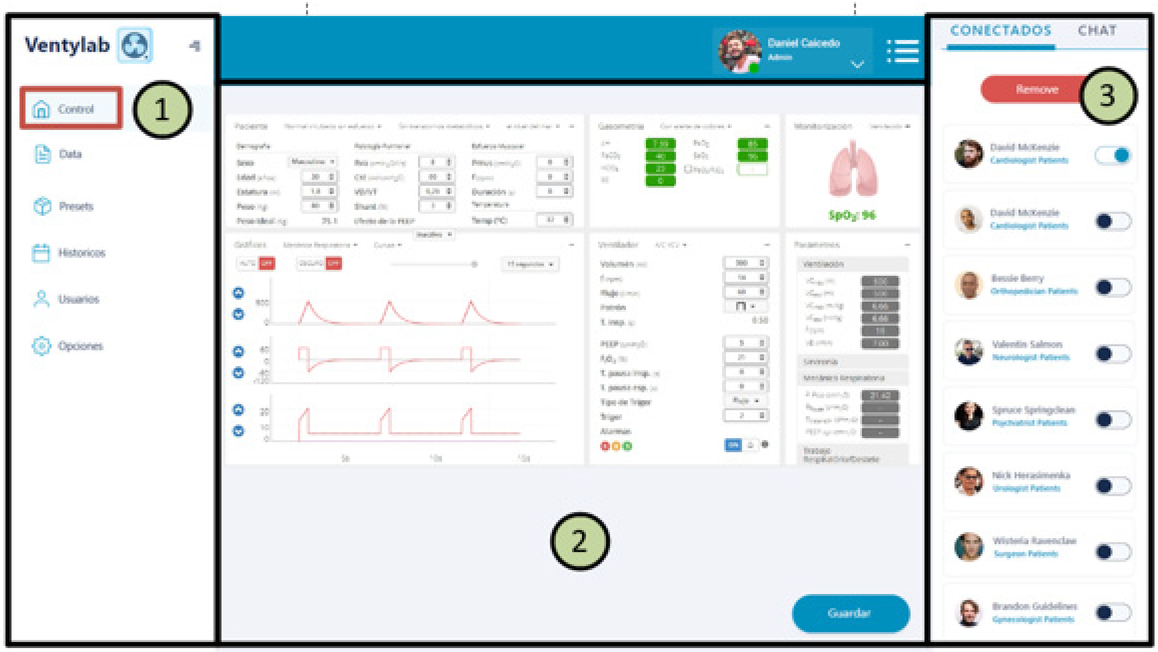

Figure 4. HMI Instructor.

Source: own elaboration

Figure 5. HMI Student.

Source: own elaboration

- **Mechanical Ventilator (MV):** This is a clinical-grade apparatus engineered to provide full or partial respiratory support for patients with compromised pulmonary function. Its operational principle involves the automated delivery of a precisely blended respiratory gas (comprising medical air and oxygen) to the patient's airways.

- **Patient emulator (PE):** A hardware unit that interfaces directly with the mechanical ventilator to simulate the biomechanical properties of the human respiratory system. Through the calibration of physiological parameters—including pulmonary compliance, tracheobronchial resistance, and circuit leakage—it can replicate a diverse spectrum of pathological pulmonary states. The design and implementation of this simulator are detailed in [41].

Variable Specification for the Remote Mechanical Ventilation Training Platform

Each entity delineated in Figure 2 is associated with a distinct set of operational variables, which are characterized as follows.

Trainee Terminal:

This interface relays ventilator configuration parameters to the central communication node. This data stream is formally represented by the variable ve(n), where the index (n) denotes the specific trainee initiating the parameter adjustment. Table 1 provides a comprehensive specification of these variables.

Table 1. *Operational variables of the Cyber-Physical System.*

Variable	Values	Description
IP	1…5	The IP address is used to facilitate the structured and secure transfer of data between devices.
sid(n)	sid(1), sid(2), …, sid(n)	Unique identifier for each student participant in the training scenario.
vpe	vpe1, vpe2, vpe3	Configuration parameters defined by the instructor for the patient emulator.
set up (data)	set up("mv1"), set up("mv2"), set up("mv3")	Configuration parameters assigned to each mechanical ventilator emulator instance is conducted.
Variables (data)	variables("vmv1"), variables("vmv2"), variables("vmv3")	The mechanical ventilator emulator generates operational variables during simulation and training.

Functional and Operational Modeling of the Remote Mechanical Ventilation Training Platform

Following the systematic characterization of the principal agents of the system and their associated operational variables, the subsequent phase involves a granular analysis of its core functionalities. This is accomplished by developing an enhanced architectural schematic that elaborates upon the initial conceptual diagram. The refined representation, presented in Figure 3, explicitly delineates the specific processes enabled by the data management subsystem within the cyber-physical architecture.

A detailed assessment of Figure 3 indicates that the information management subsystem provides comprehensive support for the following operational capacities:

a. **Real-Time Telemetry and Visualization:** The framework ensures the continuous acquisition and instantaneous graphical representation of operational telemetry from both the ventilator simulator and pulmonary emulator, presenting this data within individualized trainee consoles.

b. **Participant Connection State Supervision:** The instructor's console incorporates functionality for tracking the connection status and activity of all active trainees, providing continuous oversight throughout instructional exercises.

c. **Privilege-Based Resource Allocation:** The system enables the instructor to dynamically assign equipment control privileges to specific trainees, facilitating guided interaction with the ventilator simulator while preserving the operational security.

d. **Direct Instructor-Initiated Parameterization:** The architecture permits the instructor to directly configure operational parameters of both the mechanical ventilator and patient emulator, enabling the precise replication of complex clinical presentations.

e. **Configuration Parameter Archival:** All parameter sets applied to the ventilator simulator and patient module during training sessions are systematically recorded in a secured database, enabling post-session evaluation and performance review.

f. **Operational Response Data Capture:** The system persistently logs dynamic performance metrics generated during simulator operation, creating a comprehensive dataset for subsequent trainee competency assessment and skill progression analysis.

This rigorous functional modeling ensures that the cyber-physical system satisfies the exacting requirements of remote clinical ventilation training, delivering a resilient and scalable instructional framework.

The implemented communication architecture thereby establishes the necessary infrastructure for deploying a distributed laboratory for mechanical ventilation instruction, incorporating an integrated ventilator simulator and patient emulator to create an authentic clinical training environment. With the system's functional specifications and component interactions fully defined, the development of formal models using Petri net formalism can be commenced.

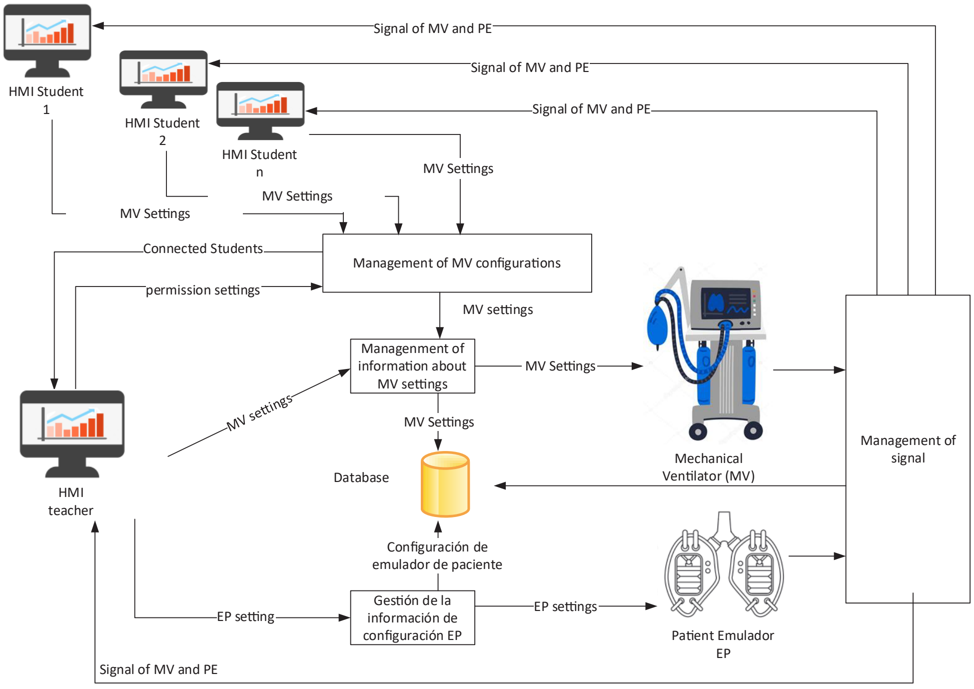

Figure 6. Comprehensive Infrastructure Diagram of the VentyLab Information Management Framework.

Source: own elaboration

Simulation Framework Employing Colored Petri Nets

A computational model was implemented to emulate the dynamic behavior of the communication infrastructure underpinning the teleoperated mechanical ventilation training system. This model is derived from the architectural topology presented in Figure 1 and incorporates the specified system variables with their associated operational logic. The formal representation was constructed using Colored Petri Nets, which provide a rigorous, event-driven methodology for capturing the system's concurrent processes and state-dependent interactions, as depicted in Figure 7.

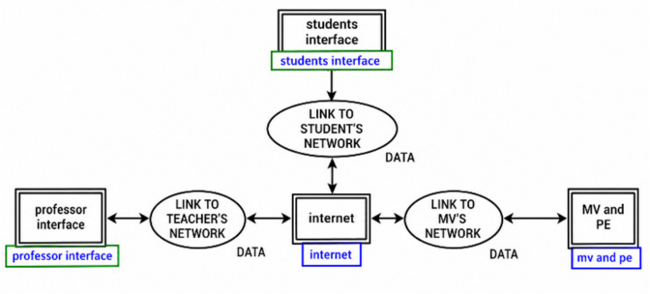

Figure 7. Model in petri nets of the interactions between system actors.

Source: own elaboration

The formulated model is architected around three principal transitions—denoted by double-bordered rectangles—which consolidate the fundamental subnets representing the Professor Interface, the Communication Network, and the integrated Mechanical Ventilator–Patient Emulator (MV–PE) unit, in addition to the Student Interfaces.

The macro-transition designated as "Professor Interface" encapsulates the subnet corresponding to the instructor's control station. This subsystem enables the professor to monitor the roster of active student sessions and grant individual permissions for remote operation of the laboratory equipment. A critical system constraint dictates that configuration and operational control of the mechanical ventilator and patient emulator are exclusively allocated to a single user at any given time, whether the professor or a designated student.

As illustrated in Figure 8, the "Professor Interface" subnet depicts a simulated state wherein three student sessions—identified as sid(1), sid(2), and sid(3)—maintain concurrent connections to the platform. Within this operational context, the professor possesses the capability to delegate specific control privileges to individual students, permitting them to modify ventilator parameters in accordance with a pre-established clinical scenario (represented by the vpe variable for the patient emulator). Conversely, the professor retains the option to directly configure the ventilator and emulator settings via the dedicated "Set up MV and PE" subnet.

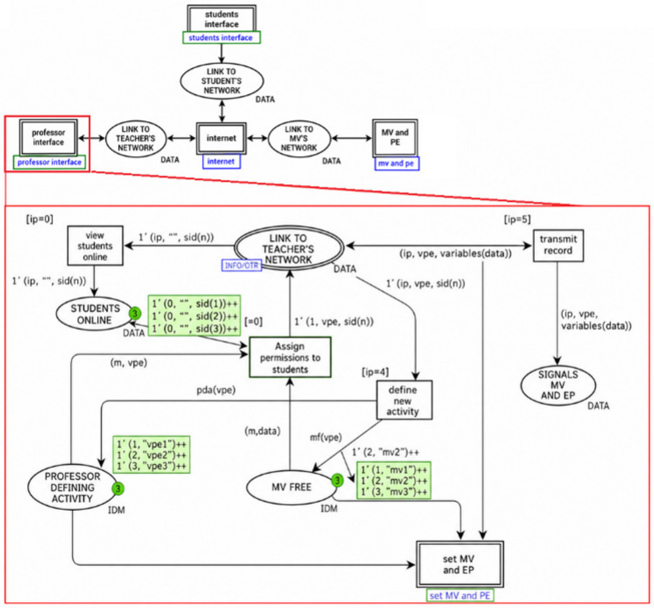

Figure 8. Subnet “professor interface"

Source: own elaboration

The macro-transition designated as "Internet," illustrated in Figure 9, orchestrates the bidirectional exchange of data between the instructional staff, trainees, and the physical hardware components. Within this architecture, control permissions issued by the professor are propagated via the communication network to individual student interfaces, maintaining synchronized state management across the distributed cyber-physical system.

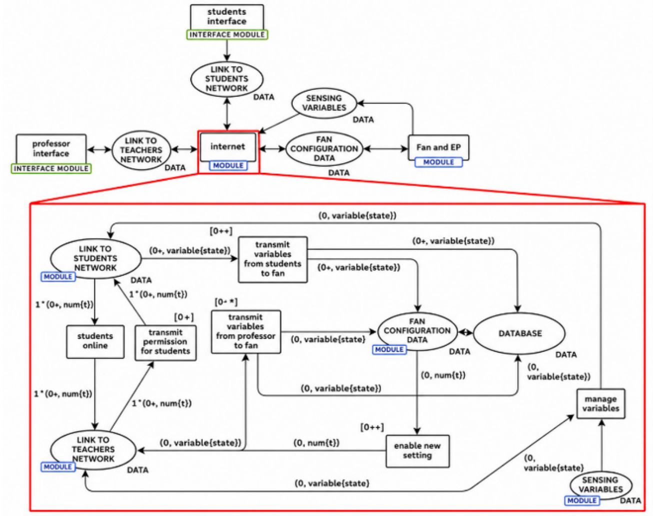

Figure 9. Subnet Internet.

Source: own elaboration

Upon authorization, each trainee configures the mechanical ventilator's operational parameters (represented by the token ip=3). These calibrated values are subsequently transmitted via the communication network to the physical laboratory apparatus, as delineated in Figure 10.

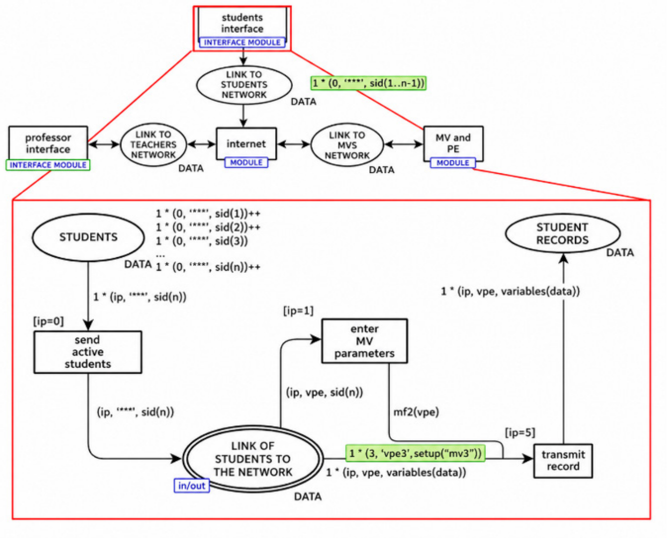

Figure 10. Subnet students interface.

Source: own elaboration

Furthermore, the Student Interface subnet aggregates the variable data streams generated by both the mechanical ventilator and the patient emulator. This functionality ensures all connected trainees can monitor the operational outputs and performance metrics of the ventilator system in real time.

The "MV and PE" subnet processes configuration data originating either from the instructor—when establishing a representative clinical scenario—or from authorized students during training exercises. This initialization phase, parameterized by directives such as set up (mv3), defines the simulated clinical case through variables modeling pulmonary respiratory mechanics, specifically pulmonary compliance and airway resistance.

This input data drives the configuration of the ventilator emulator. The resultant response variables produced by the emulator (e.g., "vmv1", "vmv2", "vmv3") are subsequently broadcast to both the instructor and student interfaces for analytical review, as illustrated in Figures 11 and 12.

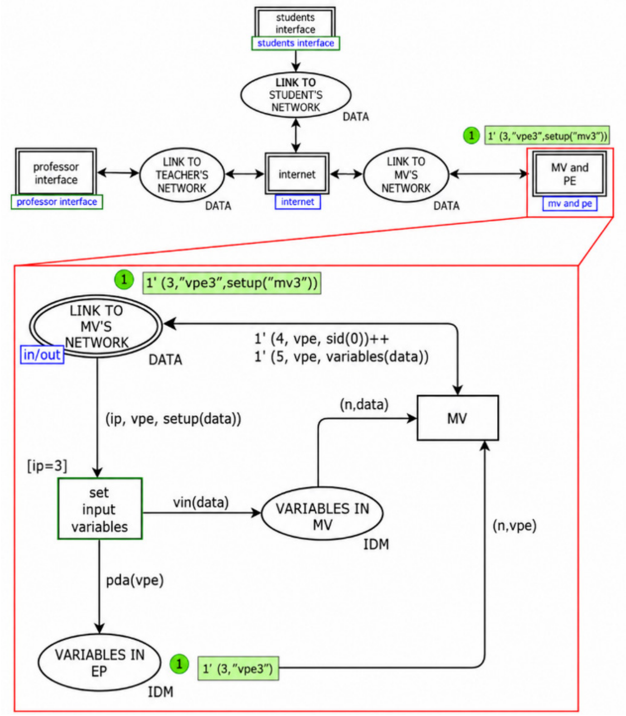

Figure 11. Subnet "MV and PE": Data Input to the Patient Emulator.

Source: own elaboration

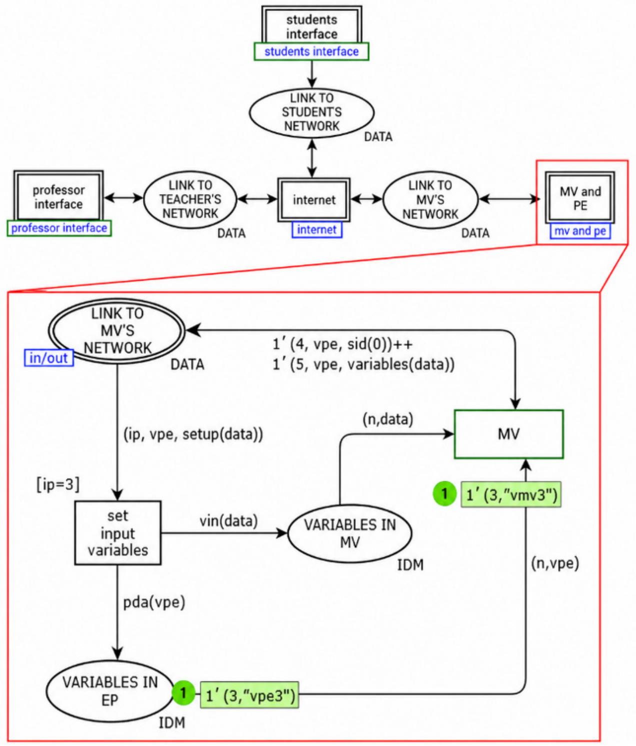

Figure 12. Subnet "MV and EP", EP's response.

Source: own elaboration

Discussion of Results

The constructed model, based on the proposed modular architecture, demonstrates a robust framework for analyzing dynamic interactions within the training ecosystem—specifically between instructional interfaces and physical simulation devices. This methodology accurately replicates operational conditions encountered in clinical mechanical ventilation scenarios.

The application of Colored Petri Nets afforded a detailed yet integrated representation of system functionality. This abstraction level enables precise identification of subsystem interdependencies, supporting both operational visualization and prediction of potential system constraints. The explicit modeling of permission structures, data acquisition pathways, and equipment responses facilitates the simulation of diverse clinical presentations, thereby enhancing training realism and educational effectiveness.

The architecture's modular nature provides significant adaptability. Modifications to specific components—such as trainee interaction protocols or device response algorithms—can be implemented without disrupting overall system integrity. This flexibility is particularly valuable in medical education, where evolving clinical demands require responsive training methodologies.

The implementation of bidirectional data exchange between interfaces and physical simulators enables real-time performance feedback for both instructors and trainees. This capability not only improves simulation fidelity but also supports comprehensive competency assessment during remote training sessions.

Future Work:

While the proposed model demonstrates a robust architectural and formal representation of the teleoperated training system, several avenues remain open for future development. From a technical perspective, it is essential to conduct stress and scalability tests of the communication network to evaluate system performance under high concurrency conditions, including latency analysis and maximum supported number of simultaneous users. These experiments would provide quantitative insights into the operational limits of the platform in real-world deployment scenarios.

Additionally, future work should incorporate a pedagogical validation of the system through controlled pilot studies involving medical trainees. Such studies would enable the assessment of learning outcomes, user interaction patterns, and the effectiveness of the platform in improving clinical decision-making skills in mechanical ventilation. The integration of learning analytics could further support the objective measurement of user performance and skill acquisition over time.

Conclusions

This research establishes a methodologically rigorous framework that integrates remote laboratory capabilities with digital learning environments through advanced information technologies. The cyber-physical model, developed using Colored Petri Nets, ensures precise specification of both architectural components and dynamic interactions between human operators and physical simulation devices.

Through systematic identification and modeling of operational parameters, the framework accurately represents all aspects of remote ventilation training—including instructional supervision, controlled trainee access, and clinical scenario emulation through parameterized respiratory mechanics.

The proposed architecture enhances system adaptability and scalability, providing a foundation for continuous refinement in response to evolving educational requirements and clinical protocols. This work holds immediate relevance for advancing clinical training in mechanical ventilation—particularly crucial in pandemic contexts and future scenarios requiring decentralized educational solutions.

In summary, this investigation establishes a comprehensive technical model that bridges theoretical simulation and practical application in medical education, creating new possibilities for high-fidelity remote training systems while strengthening clinical preparedness in ventilator management.

Acknowledgments

The author acknowledges Universidad del Valle for the financial support that enabled this research.

References

[1] J. D. Allen, "Human physiology - the basis of medicine," *Ulster Med. J.*, vol. 77, no. 3, p. 216, Sep. 2008. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2604485/

[2] Forum of International Respiratory Societies and European Respiratory Society, *The Global Impact of Respiratory Disease*. Sheffield, UK: European Respiratory Society, 2017, ISBN: 978-1-84984-087-3. [3] Global Asthma Network, *The Global Asthma Report 2014*. Auckland, New Zealand: Global Asthma Network, 2014, ISBN: 978-0-473-29125-9.

[4] P. G. J. Burney, J. Patel, R. Newson *et al.*, "Global and regional trends in COPD mortality, 1990–2010," *Eur. Respir. J.*, vol. 45, no. 5, pp. 1239–1247, May 2015. https://doi.org/10.1183/09031936.00142414

[5] N. Petrosillo, G. Viceconte, O. Ergonul *et al.*, "COVID-19, SARS and MERS: Are they closely related?" *Clin. Microbiol. Infect.*, vol. 26, no. 6, pp. 729–734, Jun. 2020. https://doi.org/10.1016/j.cmi.2020.03.026[6] N. Karamolegkos *et al.*, "Patient emulator: A tool for testing mechanical ventilation therapies," in *Proc. 38th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBC)*, IEEE, 2016. https://doi.org/10.1109/EMBC.2016.7591683

[7] G. Avendaño, F. Toncio, and P. Fuentes, "Design and construction of a real simulator for calibrating lung servo-ventilators," in *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. (EMBS)*, IEEE, 2010. https://doi.org/10.1109/IEMBS.2010.5626175

[8] AQAI, "TestChest lung simulator," AQAI GmbH. [Online]. Available: https://www.aqai.eu/en/products-service/development/testchest.php

[9] Michigan Instruments, "Lung simulators," Michigan Instruments. [Online]. Available: https://www.michiganinstruments.com/lung-simulators/

[10] R. Pasteka *et al.*, "Electro-mechanical lung simulator using polymer and organic human lung equivalents for realistic breathing simulation," *Sci. Rep.*, vol. 9, no. 1, art. 19778, pp. 1–12, 2019. https://doi.org/10.1038/s41598-019-56176-6

[11] S. Heili-Frades, G. Peces-Barba, and M. J. Rodríguez-Nieto, "Design of a lung simulator for teaching lung mechanics in mechanical ventilation," *Arch. Bronconeumol. (Engl. Ed.)*, vol. 43, no. 12, pp. 674–679, 2007. https://doi.org/10.1016/S1579-2129(07)60154-2

[12] MA Horvath *et al.* , "Un simulador respiratorio robótico blando organosintético", *APL Bioengineering* , vol. 4, n.º 2, pág. 026108, junio de 2020, https://doi.org/10.1063/1.5140760

[13] Laerdal Medical, "ASL 5000 lung solution," Laerdal Medical. [Online]. Available: https://laerdal.com/de/information/shortcuts-and-redirects/ASL5000-LungSolution/

[14] R. Paštěka and M. Forjan, "Actively breathing mechanical lung simulator development and preliminary measurements," in *EMBEC & NBC 2017*, Singapore: Springer, 2017, pp. 751–754. https://doi.org/10.1007/978-981-10-5122-7_188

[15] F. Bautsch, G. Männel, and P. Rostalski, "Development of a novel low-cost lung function simulator," *Curr. Dir. Biomed. Eng.*, vol. 5, no. 1, pp. 557–560, 2019. https://doi.org/10.1515/cdbme-2019-0140

[16] S. Heili-Frades, G. Peces-Barba, and M. J. Rodríguez-Nieto, "Diseño de un simulador de pulmón para el aprendizaje de la mecánica pulmonar en ventilación mecánica," *Arch. Bronconeumol.*, vol. 43, no. 12, pp. 674–679, 2007. https://doi.org/10.1157/13112966 [17] H. S. Johar and K. Yadav, "DRDO's portable low-cost ventilator: 'DEVEN'," *Trans. Indian Natl. Acad. Eng.*, vol. 5, no. 2, pp. 365–371, 2020. https://doi.org/10.1007/s41403-020-00143-5

[18] J. Saiful *et al.*, "Design and implementation of ventilator for breathing apparatus," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 990, no. 1, art. 012007, 2020. https://doi.org/10.1088/1757-899X/990/1/012007

[19] B. El Majid *et al.*, "Preliminary design of an innovative, simple, and easy-to-build portable ventilator for COVID-19 patients," *Euro-Mediterr. J. Environ. Integr.*, vol. 5, art. 57, pp. 1–4, 2020. https://doi.org/10.1007/s41207-020-00163-1

[20] J. M. Knorr *et al.*, "Design and performance testing of a novel emergency ventilator for in-hospital use," *Can. J. Respir. Ther.*, vol. 56, art. 42, 2020. https://doi.org/10.29390/cjrt-2020-023

[21] A. Darwood *et al.*, "The design and evaluation of a novel low-cost portable ventilator," *Anaesthesia*, vol. 74, no. 11, pp. 1406–1415, 2019. https://doi.org/10.1111/anae.14726

[22] A. Vasan *et al.*, "MADVent: A low-cost ventilator for patients with COVID-19," *Med. Devices Sens.*, vol. 3, no. 4, art. e10106, 2020. https://doi.org/10.1002/mds3.10106

[23] F. J. Vivas Fernández *et al.*, "ResUHUrge: A low cost and fully functional ventilator indicated for application in COVID-19 patients," *Sensors*, vol. 20, no. 23, art. 6774, 2020. https://doi.org/10.3390/s20236774

[24] J. Tharion *et al.*, "Rapid manufacturable ventilator for respiratory emergencies of COVID-19 disease," *Trans. Indian Natl. Acad. Eng.*, vol. 5, pp. 373–378, 2020. https://doi.org/10.1007/s41403-020-00118-6 [25] A. Petsiuk *et al.*, "Partially RepRapable automated open source bag valve mask-based ventilator," *HardwareX*, vol. 8, art. e00131, 2020. https://doi.org/10.1016/j.ohx.2020.e00131.

[26] S. H. Sojar *et al.*, "Titration of parameters in shared ventilation with a portable ventilator," *Respir. Care*, vol. 66, no. 5, pp. 758–768, 2021. https://doi.org/10.4187/respcare.08446

[27] C. Galbiati *et al.*, "Mechanical Ventilator Milano (MVM): A novel mechanical ventilator designed for mass scale production in response to the COVID-19 pandemics," *medRxiv*, preprint, 2020. https://doi.org/10.1101/2020.03.24.20042234

[28] J. Živčák *et al.*, "A portable BVM-based emergency mechanical ventilator," in *Proc. 19th IEEE World Symp. Appl. Mach. Intell. Informatics (SAMI)*, IEEE, 2021. https://doi.org/10.1109/SAMI50585.2021.9378620 [29] S. M. Mirvakili, D. Sim, and R. Langer, "Inverse pneumatic artificial muscles for application in low-cost ventilators," *Adv. Intell. Syst.*, vol. 3, no. 1, art. 2000200, 2021. https://doi.org/10.1002/aisy.202000200

[30] S. Mora, F. Duarte, and C. Ratti, "Can open source hardware mechanical ventilator (OSH-MVs) initiatives help cope with the COVID-19 health crisis? Taxonomy and state of the art," *HardwareX*, vol. 8, art. e00150, 2020. https://doi.org/10.1016/j.ohx.2020.e00150

[31] R. M. Kacmarek, "The mechanical ventilator: Past, present, and future," *Respir. Care*, vol. 56, no. 8, pp. 1170–1180, 2011. https://doi.org/10.4187/respcare.01420

[32] J. Chang *et al.*, "Masi: A mechanical ventilator based on a manual resuscitator with telemedicine capabilities for patients with ARDS during the COVID-19 crisis," *HardwareX*, vol. 9, art. e00187, 2021. https://doi.org/10.1016/j.ohx.2021.e00187

[33] A. Takeuchi *et al.*, "Interactive simulation system for artificial ventilation on the internet: Virtual ventilator," *J. Clin. Monit. Comput.*, vol. 18, no. 5, pp. 353–363, 2004. https://doi.org/10.1007/s10877-005-6268-0

[34] N. Ambrosino *et al.*, "Tele-monitoring of ventilator-dependent patients: A European Respiratory Society Statement," *Eur. Respir. J.*, vol. 48, no. 3, pp. 648–663, 2016. https://doi.org/10.1183/13993003.01721-2015

[35] Y. Li *et al.*, "A Petri net based model for a cloud healthcare system," in *Proc. Chinese Control and Decision Conf. (CCDC)*, IEEE, 2018. https://doi.org/10.1109/CCDC.2018.8407805 [36] S. Mtibaa and M. Tagina, "An automated Petri-net based approach for change management in distributed telemedicine environment," arXiv preprint arXiv:1210.6076, 2012. [Online]. Available: https://arxiv.org/abs/1210.6076

[37] I. Ruiz, J. Contreras, and J. Garcia, "Towards a physical rehabilitation system using a telemedicine approach," *Comput. Methods Biomech. Biomed. Eng.: Imaging Vis.*, vol. 9, no. 4, pp. 354–363, 2020. https://doi.org/10.1080/21681163.2020.1795929

[38] F. J. Mejia, J. I. Garcia, and C. E. Hurtado, "Model-based design of body motion sensing technology using systems modeling language and coloured Petri nets," in *Proc. IEEE Int. Conf. E-health Netw. Appl. Serv. (HealthCom)*, IEEE, 2019. https://doi.org/10.1109/HealthCom46333.2019.9009430

[39] K. Collante, "Guía completa para crear tu diagrama de infraestructura," Hackmetrix Blog, Aug. 19, 2021. Accessed: Nov. 19, 2021. [Online]. Available: https://blog.hackmetrix.com/como-hacer-un-diagrama-de-infraestructura/

---

[40] J. M. Rosen *et al.*, "Telehealth's new horizon: Providing smart hospital-level care in the home," *Telemed. e-Health*, vol. 27, no. 11, pp. 1215–1224, 2021. https://doi.org/10.1089/tmj.2020.0448

[41] A. M. Valencia, I. Ruiz, J. I. García, and A. Galvis, "Design of a patient simulator for clinicians training in mechanical ventilation: SimVep," *J. Med. Eng. Technol.*, vol. 49, no. 3, pp. 79–92, 2025. https://doi.org/10.1080/03091902.2025.2484672