

Digital Twin Experimentation to Evaluate the Complementarity Between Lean Maturity and Industry 4.0 Adoption

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Abstract

The heterogeneous performance outcomes observed in Industry 4.0 implementations suggest that technological adoption alone does not guarantee operational improvement. This study proposes a digital twin-based experimental framework integrating factorial design and moderated regression modeling to assess the complementarity between Industry 4.0 adoption and Lean maturity. A full factorial 2^3 digital twin experimental structure was developed to simulate automation level, workforce training, and process standardization under stochastic operational variability. Moderated regression analysis was conducted to evaluate whether Lean maturity amplifies the marginal effect of Industry 4.0 adoption on operational performance. Results indicate significant main and interaction effects at the operational level, while moderation analysis confirms a strong positive amplification effect ($\Delta R^2 = 0.088$, $p < 0.001$). Effect size analysis and bootstrap robustness tests further validate the findings. The study contributes by integrating experimental design and capability-based moderation modeling within a digital twin framework, offering insights for digital transformation sequencing strategies.

Keywords

Digital Twin, Industry 4.0, Lean Maturity, Moderation Analysis, Factorial Design.

Biographies

Dr. Mauricio Torres Torres is a full-time professor at the Facultad de Ciencias Químicas of the Universidad Autónoma de Nuevo León (UANL), Mexico, where he has more than 15 years of teaching experience. He teaches undergraduate and graduate courses in Probability, Statistics, Design of Experiments, Operations Research, and Quantitative Methods for decision-making. He received his bachelor's degree in mathematics from the Facultad de Ciencias Físico Matemáticas (FCFM) at UANL in 2006. He earned a master's degree in education from Universidad Tecmilenio, Nuevo León, Mexico, in 2010, and a second master's degree in Industrial Engineering with a specialization in Service Design and Optimization from the Facultad de Ciencias Químicas at UANL in 2018. He completed his Ph.D. in Industrial Physics Engineering at FCFM, UANL, in 2021. His research interests include mathematical modeling, optimization of industrial systems, digital transformation in manufacturing, and the development of fiber-optic sensor devices. He is currently engaged in academic research and interdisciplinary projects aimed at improving efficiency and innovation in engineering and applied sciences. He is a Candidate Level member of the Sistema Nacional de Investigadores (SNI).

Azucena Minerva García-León is received the Bachelor of Science degree in industrial engineering and the Master of Science degree in industrial engineering from the *Universidad de las Américas-Puebla*, the master's degree in industrial engineering from the *Institut National Polytechnique de Grenoble* (INPG), France, the Ph.D. degree in applied economics from the *Université Grenoble Alpes* (UGA), France, and the Postgraduate degree in data science and machine learning from the Business School of Innovation and Entrepreneurship (IEBS), Spain. She was a process and reliability specialist Engineer at the *Instituto Mexicano del Petróleo* (IMP), Institutional Region of the Marine Zone, Campeche, Mexico, performing qualitative and quantitative risk analysis, reliability analysis, and process optimization in marine production complexes. She was the Chair of the Master's in Industrial Engineering Program and the Master's in Analytics and Digital Transformation of Business Program at UANL. Is currently a full-time Professor and a Researcher with the School of Chemical Sciences, *Universidad Autónoma de Nuevo León* (UANL), in the undergraduate and graduate programs of industrial engineering. She is a member with the *Sistema Nacional de Investigadoras e Investigadores* (SNII) and the Design and Optimization of Production Systems Research Group. She has published papers in indexed and peer-reviewed journals, books, book chapters, and conferences. She has participated as a speaker at national and international conferences, contributing to the dissemination and divulgation of research. She provides instruction to the industrial sector in Lean Sigma for Green Belt and Black Belt certifications and promotes university-industry vinculation. She is a Researcher in the fields of risk analysis, lean manufacturing, six sigma, experimental analysis and design, reliability, and production process optimization. She has directed and co-directed master's and Ph.D. theses. She is an Accredited Evaluator of the registry of the *Consejo Nacional de Humanidades, Ciencias y Tecnologías* (CONAHCYT).

Dr. Eli González-Trejo holds a Ph.D. in International Business Administration and an MBA from Texas A&M International University. His professional experience includes the areas of sales, marketing, and customer service. He is currently a full-time professor and the Academic Deputy Director of the Industrial Engineering and Management program at Universidad Autónoma de Nuevo León, where he teaches courses such as Strategic Planning, Introduction to Management, Sales Management and Coaching, Organizational Behavior, and Leadership, among others. Dr. González has been recognized by the Secretaría de Educación Pública with the PRODEP profile. He is a Candidate Level member of the Sistema Nacional de Investigadores (SNI) and is also a member of the Institute of Industrial and Systems Engineers (IISE) and the Instituto Mexicano de Ingenieros Industriales y de Sistemas (IMIIS).

Soraya Concepción Elizondo-Jiménez is a full-time professor at the Faculty of Chemical Sciences of the Autonomous University of Nuevo León (UANL), Mexico, where she has more than 22 years of teaching experience. She teaches courses in Statics and Laboratory, Classical Physics and Laboratory, and Information Technology. She received her Bachelor's degree in Administrative Engineering and Systems from the Faculty of Mechanical and Electrical Engineering (FIME) at UANL in 1991. She obtained a Master's degree in Administration with a specialization in Human Resources from the Graduate School of the Faculty of Chemical Sciences at UANL, Nuevo León, Mexico, in 2004. She completed her Ph.D. in Strategic Management at the International Educational Consortium WARDEN, A.C., in 2025. Her research interests include the optimization of industrial management systems, the digital era in higher education, and the teaching of physics at the university level. She is currently involved in academic research and interdisciplinary projects aimed at improving efficiency and innovation in engineering and applied sciences.