Proceedings of the 2nd World Congress on Industrial Engineering and Operations Management
Windsor, Canada, October 14-16, 2025

Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/WC02.20250116
Published: October 14, 2025

Quantifying Factor Impacts on Exact Neural Network Verification with Mathematical Programming

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Abstract

Exact verification of deep neural networks (DNNs) is critical for safety- and reliability-sensitive manufacturing and supply chain applications, including automated defect detection in assembly lines, predictive maintenance scheduling, and digital twins. In such contexts, verification must guarantee that models behave predictably under all admissible inputs, minimizing costly downtime or defective output. This study presents a large-scale, controlled experiment to quantify how architectural and training factors influence end-to-end verification time using Mixed-Integer Linear Programming (MILP). We trained 500 feed-forward neural networks under a full-factorial design spanning four factors: hidden layer count, neurons per layer, regularization method, and number of training epochs, replicated across five random seeds. For each trained model, we measured compute times across the complete verification pipeline: model training, verification model construction, and MILP solving. Factor contributions and interactions were isolated using Linear Mixed-Effects (LME) and Logistic Regression (LR) models, enabling precise attribution of verification cost drivers. Two leading LP-based bound-propagation formulations were benchmarked, with the compact Δ-relaxation approach consistently outperforming alternatives. We further quantified the advantages of LP-based bounds over interval arithmetic, showing tighter bounds that improved neuron stability and reduced solving complexity. Finally, a new MILP solving strategy reduced average verification timeouts from 59% to 5%, offering a path toward predictable and scalable verification in industrial AI deployments.

Keywords
Neural Net Verification, Mixed Integer Linear Programming, Trustworthy AI, Adversarial Robustness, Experimental Design.

Biographies
Konstantinos Ziliaskopoulos received his BS and MS in Electrical & Computer Engineering from the Aristotle University in Thessaloniki, Greece in 2021. He is a Ph.D. candidate in the Dept. of Industrial & Systems Engineering at Auburn University. His research interests include the intersection of data analytics and artificial intelligence with the fields of Operations Research and mathematical programming.

Alice E. Smith is the Joe W. Forehand, Jr. Distinguished Professor of the Industrial and Systems Engineering Department at Auburn University. Her research focus is analysis, modeling, and optimization of complex systems with emphasis on computation inspired by natural systems integrated with traditional operations research and statistical approaches. She holds one U.S. patent and several international patents and has authored publications which have garnered over 18,000 citations, an H Index of 51, and an i10 Index of 129 (Google Scholar). Dr. Smith has been a principal investigator on over $12 million of sponsored research with funding by Department of Homeland Security, NASA, U.S. Department of Defense, Missile Defense Agency, National Security Agency, NIST, U.S. Department of Transportation, Frontier Technologies Inc., Lockheed Martin, Adtranz (now Bombardier Transportation), the Ben Franklin Technology Center of Western Pennsylvania, and U.S. National Science Foundation, from which she has been awarded 18 distinct grants including a CAREER grant and an ADVANCE Leadership grant. Dr. Smith is a member of the National Academy of Engineering (NAE), a Life Fellow of the Institute of Electrical and Electronics Engineers (IEEE), a Fellow of the Institute for Operations Research and Management Science (INFORMS), a Fellow of the Institute of Industrial and Systems Engineers (IISE), a senior member of the Society of Women Engineers, a member of Tau Beta Pi, and a Registered Professional Engineer.