Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/WC02.20250244
Published: October 14, 2025

Towards Sustainable Human-Robot Collaborative Assembly: A framework Integrating Time, Safety, and Energy Efficiency

Mahboobe Kheirabadi, Samira Keivanpour, Yuvin Chinniah and Jean-Marc Frayret
Department of Mathematics and Industrial Engineering
Polytechnique Montreal
Montreal, Canada
Mahboobe.kheirabadi@polymtl.ca, Samira.keivanpour@polymtl.ca,
Yuvin.chinniah@polymtl.ca, Jean-marc.frayret@polymtl.ca

Abstract

The integration of collaborative robots (cobots) into assembly systems has transformed manufacturing by enabling flexible, adaptive, and human-centered production environments. However, designing and managing human–robot collaborative assembly lines remain a complex task, as multiple objectives must be balanced simultaneously. This paper addresses three interrelated dimensions: time efficiency, safety, and energy consumption. Time remains a critical drive of productivity, where synchronization of human and robot tasks directly influences cycle time and throughput. Safety is essential due to the shared workspace in which task allocation, interaction mode, and robot end effector and speed can either mitigate or intensify physical and mental risks to workers. Although cobots are typically more energy-efficient than traditional industrial robots, their cumulative energy use becomes significant at scale, particularly when deployed across multiple stations or operating continuously. Moreover, energy consumption is not independent: shorter cycle times often require higher accelerations and power demands, while slower, safety-oriented operations may reduce energy use but extend production duration. These interdependencies highlight the importance of considering energy not as a marginal factor, but as part of a broader trade-off with time and safety. Building on this perspective, a mathematical model is developed to integrate these objectives into a unified framework for human–robot collaborative assembly. The contribution lies in advancing beyond single-objective optimization to capture the inherent trade-offs, offering insights that are aligned with emerging sustainability and safety standards. This approach provides a basis for future empirical validation and supports the development of resilient and sustainable human–robot collaborative systems.

Keywords

Human-Robot Collaboration, Collaborative Assembly, Safety Risk, Sustainability, Energy consumption, Cobots, Multi-Objective Optimization, Industry 5.0

Biographies

Mahboobe Kheirabadi is a Ph.D. candidate in the Department of Mathematical and Industrial Engineering at Polytechnique Montréal, Canada. Her research is centered on developing methodologies to improve the efficiency of human–robot collaboration in assembly lines. By investigating strategies to prevent accidents and optimize the performance of collaborative settings, she aspires to contribute to the advancement of smart manufacturing systems while prioritizing occupational health and safety.

Samira Keivanpour is an Associate Professor of Mathematical and Industrial Engineering at Polytechnique Montreal, Canada, and heads the Poly Circle X.0 lab. Her research focuses on sustainable manufacturing and logistics within the framework of Circular Economy X.0. She explores the application of ML/RL for enhancing triple bottom line

(3BL) impact, with applications in end-of-life products, circular manufacturing, and Industry 4.0 technologies to drive sustainable solutions. She is a member of CIRODD, GERAD, and CIRRELT.

Yuvin Chinniah is a Professor of Industrial Engineering and a PEng in Quebec, Canada. His area of expertise includes safety of fixed and mobile machinery, risk assessment and risk reduction, robots' safety as well as cobots safety, OHS regulations and standardization, safety in confined spaces, control of hazardous energies and safe design of equipment. Dr Chinniah has been working in the OHS area since 1997. He worked as a safety engineer for two years, as a research scientist for five years at the IRSST in Montreal and has been a faculty member at Polytechnique Montreal since 2009. His is the author and co-author of 150 peer reviewed articles in journals, conference proceedings and IRSST scientific reports. He was the Canadian chair in the TC199 ISO committee on safety of machinery and an expert in several working groups in ISO and CSA. Dr. Chinniah has been the chair of the Department of Mathematics and Industrial Engineering at Polytechnique Montreal since 2019.

Jean-Marc Frayret is a professor of Industrial Engineering, specializing in the design and operations of complex logistic systems. With extensive expertise in modelling and simulation, his research focuses on complex value chain ecosystems, applying simulation and operations research to value chains, circular economy, end-of-life product collection, urban mobility and manufacturing operations. His ongoing projects involve Advanced Air Mobility (AAM), where he explores sustainable solutions for the future of Electric Air Mobility. He co-leads the SDG AAM institute and supervises 12 graduate students. In 2013, he was awarded the Brockhouse Canada Prize for Interdisciplinary Research in Science and Engineering from Natural Sciences and Engineering Research Council of Canada. He is also actively engaged in the scientific committee of the Interuniversity Research Centre for the Operationalization of Sustainable Development and was co-chair of the 2024 IISE Annual Conference in Montreal.