Integrated Optimization and Digital Twin Approaches for Sustainable Human-Centred Collaborative Assembly Lines in Industry 5.0

Bahir Hind

CERI SN Laboratory, IMT Nord Europe, Douai - France
hind.bahir@imt-nord-europe.fr

Abstract:

One of the growing concerns of manufacturers in industrial production is the automation of some tasks, while ensuring the workers safety and enhancing productivity. This is where begins the important role of collaborative robots (cobots).

Cobots are the new generational robots, that are characterized by inherent security measures (Christian Weckenborg, 2019). Therefore, human-robot collaboration (HRC) is one of Industry 5.0 novel trends that worries about having sustainable, resilient, and human-centric manufacturing systems. This collaboration combines advantages of both resources; humans' creativity, flexibility and adaptability to changes, and robots' precision and immunity to fatigue which gives them ability to handle standardized and repetitive tasks (Zhaofang Mao, 2024).
In this context, my PhD research focuses on the design and optimization of Collaborative Assembly Lines (CALs) in a way that enhances ergonomics, reduces energy consumption, and ensures operational flexibility.

A critical aspect is the Assembly Line Balancing Problem (ALBP). In traditional ALBPs, tasks are allocated to workstations with the aim of optimizing productivity or minimizing cycle time, assuming homogeneous workers and deterministic processing times and performed manually by human operator, leading to significant workers' physical strain and fatigue (Ali Keshvarparast, 2024). However, Collaborative Assembly Lines (CAL) in Industry 5.0 introduce heterogeneity in agents, task processing flexibility, and multi-dimensional objectives, which require a more integrated and adaptive approach to modelling and solving. In addition, in CAL, workers and robots share the same workstation, thus resulting in different scenarios depending on how they work together to perform tasks (Ali Keshvarparast, 2024) :

- Independent: either a robot or a human operator is assigned to the workstation.
- Sequential: both the human operator and robot share the same station, doing two distinct tasks on the same workpiece.
- Simultaneous: both the human operator and robot work simultaneously on two different tasks in the same workstation.
- Supportive: both the human operator and robot work on the same task in the same workstation.

To address these challenges, this thesis comes with the aim to optimize task and resource allocation in assembly lines integrating human workers and robots, considering different collaborative modes to enhance efficiency and ergonomics. It seeks to minimize energy consumption by planning task timing and sequencing, incorporating real-time energy pricing to schedule high-energy tasks when costs are lower. Utilizing optimization and simulation techniques (such as MILP models, metaheuristics, and discrete-event simulation), and implementing Digital Twin technology with real-time data, the study intends to develop efficient, adaptable assembly lines aligned with the human-centred principles of Industry 5.0.

As a start, I have enhanced the bi-objective mixed-integer linear programming (MILP) model (Mohammed-Amine Abdous, 2025 (to be published)), which includes:

- Cost and energy consumption optimization.
- Precedence, assignment, and synchronization constraints
- Collaboration mode constraints

The contribution is done by integrating a new Simultaneous Mode (SIM), in which both human and robot perform different tasks at the same station in parallel, while still respecting inter-task dependencies. In addition, I introduced start and finish times for tasks and developed advanced synchronization constraints.

The model is solved using the ε-constraint method, allowing us to generate Pareto-optimal solutions that trade-off between energy consumption and total cost. The model is implemented in Python using PuLP.

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Références

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