An integrated model for sustainable assembly line design: a focus on resource circularity and workforce efficiency

Hamidreza Rezaei, Simon Thevenin, Audrey Cerqueus

IMT Atlantique, LS2N-CNRS, La Chantrerie, 4 rue Alfred Kastler, Nantes, France
{hamidreza.rezaei, simon.thevenin, audrey.cerqueus}@imt-atlantique.fr

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1 Introduction

In the face of intense global competition, dynamic product variations, and rapid technological developments, manufacturing systems need to adapt to market changes quickly. These frequent line reconfigurations have a negative impact on sustainability. First, frequent replacement of equipment leads to their premature end of life. Second, the constant change of technologies puts pressure on technicians who constantly learn to maintain and operate new machinery. Our work investigates approaches to the design of sustainable assembly lines by accounting for their entire life cycle at the design stage.

While the challenges of line balancing and line design have been the focus of decades of research [e.g., 1, 2], the challenge of designing adaptable lines, that can easily reconfigure to meet the evolving needs of the manufacturing landscape, has only been recently addressed [3, 4]. Considering the circularity of resources during the re-balancing of the line presents an additional challenge. While the decision-making process for equipment selection has been a subject of study in the literature [e.g., 5], there is a lack of research considering the incorporation of second-hand equipment in the context of assembly line balancing. The incorporation of resource circularity, which enables the use of second-hand resources, holds great promise for contributing to sustainable manufacturing by extending resource life cycles. Still, there is a lack of publications that address this issue in the design and balancing of the assembly line.

Workforce management is another study subject that can be addressed while developing and balancing an assembly line. Research on human aspects in industrial system design and management has grown since the early 2000s [6]. Accounting for worker profiles, learning and forgetting effects, and performance differences can improve ergonomics. Knowing and accounting for worker profiles can improve assembly line efficiency, reduce fatigue, and enhance job satisfaction. In this setting, new assembly line design models and methods are needed. These models should promote efficiency, scalability, and flexibility to accommodate different worker profiles. This guarantees that every worker is given a role that maximizes their potential, boosting assembly line productivity and efficiency.

2 Contribution

We formulate as a deterministic Mixed Integer Linear Programming (MILP) mathematical model the sustainable assembly line design problem. The considered model integrates various variables related to the characteristics of individual production resources and optimizes their arrangement within a production line configuration. This model aims to improve production efficiency and operational effectiveness while minimizing costs. The model includes three main

decisions: (i) assembly line design/redesign, (ii) equipment selection, and (iii) workforce management.
Beyond the primary goal of efficient production and overcoming line-balancing challenges, our model strives to promote sustainability across economic, environmental, and social dimensions by maximizing the reuse of production resources. Economically, it ensures that assembly lines maintain the desired throughput at minimum cost. Environmentally, it maximizes the utilization of used equipment, thereby extending its life. On the societal front, the model improves working conditions by taking into account workers' skills.

We use the commercial solver IBM ILOG CPLEX to validate the proposed mathematical model on a diverse set of generated instances. Given the complexity of the model, we present the results of two solution approaches: (1) a large model that considers all decisions simultaneously, (2) a hierarchical approach addressing the decisions sequentially - starting with line design, followed by equipment selection, and concluding with workforce management. Finally, we provide a comparison of the two approaches.

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