

## From Fatigue Models to Factory Floors: An Experimental Design for Human-Centered Production Scheduling in Industry 5.0

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The Industry 5.0 paradigm, as promoted by the European Union, places human-centricity, sustainability, and resilience at the core of industrial development. In this context, worker well-being is no longer a secondary concern but an integral component of a broader equilibrium between economic productivity and profitability, environmental constraints, and social sustainability. Among the factors affecting this balance, fatigue — encompassing its physical and cognitive dimensions — plays a central role. Fatigued workers are more prone to errors, slower cycle times, and increased injury risk, all of which degrade both the human and economic aspects of production. Yet, despite a growing body of literature on fatigue modeling and physiological fatigue measurement, a significant gap remains: no experimental work has been conducted to demonstrate, in a real production environment, that integrating real-time worker fatigue estimation into production organizations can simultaneously enhance worker well-being and industrial performance. Addressing this gap requires models capable of jointly capturing learning and fatigue dynamics — where experience accumulation and skill development interact with cognitive load, physical strain, and recovery cycles — so that performance can be described as a time-dependent, human-centered process rather than a static parameter. When informed by real-time data, such models enable simultaneous multi-dimensional optimization of economic performance, technical quality, and human sustainability.

Existing research provides valuable building blocks. The learning-forgetting-recovery framework proposed by Jaber et al. (2013) established the theoretical relationship between fatigue, recovery, and worker learning curves, highlighting the fundamental optimization trade-off between physical recovery and cognitive forgetting during rest periods. Asadayoobi et al. (2021) further refined this by incorporating fatigue effects into learning curve models. More recently, Asadayoobi et al. (2023) explored optimizing stochastic task allocation and scheduling plans for mission workers subject to learning-forgetting, fatigue-recovery, and stress-recovery effects, and Hu et al. (2025) studied AI-based flexible job-shop scheduling that accounts for worker fatigue, while Park et al. (2023) demonstrated the feasibility of real-time fatigue assessment using smartwatch-derived heart rate data. However, most current contributions remain either theoretical, simulation-based, or limited to fatigue measurement without closing the loop between fatigue estimation, scheduling decisions, and measurable production outcomes.

This work presents a comprehensive experimental protocol designed to bridge this gap. The proposed framework is fully quantitative and aims to test the hypothesis that incorporating online estimates of worker fatigue into production scheduling yields measurable improvements in the aforementioned multi-dimensional metrics. The protocol is designed for deployment in a production-line environment with machine operators, though it is intended to be generalizable to other industrial settings.

The experimental design rests on three pillars. First, real-time fatigue estimation based on wearable devices and non-invasive sensors — specifically smartwatches capturing heart rate reserve (%HRR) and heart rate variability data, and cameras capturing percentage of eye closure (PERCLOS). This builds on and extends the work of Park et al. (2023), who relied solely on heart rate, by incorporating heart rate variability as an additional physiological indicator of fatigue state. Second, validated self-report questionnaires administered at defined intervals to cross-validate the physiological fatigue estimates against workers' subjective experience. Third, production performance measurements — including but not limited to throughput, defect rates, and cycle times — collected in parallel to establish the link between fatigue-aware scheduling and operational outcomes.

Crucially, this data drives a closed-loop scheduling system. The experimental logic triggers specific interventions based on detected fatigue states, including the insertion of dynamic breaks tailored to strike a balance between necessary fatigue recovery and the avoidance of the forgetting effect, operator reassignments and rotations, and real-time adjustments to production batch sizes. A preliminary numerical simulation phase, acting as a Proof of Concept (PoC), is also planned upstream of the field experiment. To compensate for the initial lack of field data, this simulation is calibrated using standard, literature-validated parameters for fatigue accumulation and learning rates. This simulation will serve to establish candidate scheduling strategies informed by online fatigue estimates, thereby narrowing the experimental conditions to be tested on the shop floor.

Given the European context in which this research is conducted, the experimental protocol has been developed in strict compliance with the applicable ethical and legal framework. This includes adherence to the General Data Protection Regulation (GDPR) for all physiological and personal data collected, informed consent protocols ensuring workers' voluntary and fully informed participation, data anonymization procedures, and measures to mitigate the risk of perceived surveillance in the workplace, actively addressing the privacy and social acceptability barriers emphasized in the European Industry 5.0 roadmaps. Ethics committee approval will be sought prior to any data collection.

The contribution of this work is threefold. First, it proposes a structured experimental protocol specifically designed to test the integration of real-time fatigue monitoring into production scheduling in an industrial setting. Second, it addresses the full chain from measurement to decision-making to performance evaluation. Third, it embeds ethical and legal considerations as integral components of the experimental design rather than afterthoughts, consistent with the human-centered values of Industry 5.0.

If validated, the proposed approach could inform new work scheduling standards in production industries, shifting from fixed-schedule paradigms to adaptive, fatigue-aware organization of work. This represents a concrete pathway toward the Industry 5.0 vision: improving industrial competitiveness not at the expense of workers, but through their well-being. Future research will focus on implementing the protocol in a partner production facility and analyzing the resulting data.

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