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Optimizing Resource Allocation in the Flexible Job Shop Problem: Assessing the Impact of Rest Breaks on Task Strenuousness Reduction

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Abstract—The integration of collaborative robots (cobots) in production workshops aims to enhance productivity while minimizing physical strain for human operators. However, physical strain is often treated merely as a constraint rather than as an objective to address. To effectively model the production process and incorporate human factors, it is crucial to employ an appropriate index that accounts for precise ergonomic rules.

In this paper, we propose a method to organize induced waiting times in the context of Flexible Job Shop Scheduling (FJSP) with the primary goal of evaluating the effects of rest breaks on fatigue generated by physical efforts in various operations. Our method introduces a specific index, based on ergonomic standards, to assess the difficulty level of operations for both humans and robots. The index incorporates normalized strain values, ensuring its generalizability across diverse industries. Moreover, the method considers a wide range of work scenarios, encompassing both individual and collaborative settings, making it applicable to different industrial contexts. Furthermore, we analyze the accumulated fatigue experienced by human agents over several scenarios, both before and after the optimization process. By doing so, we not only gain insights into the production process but also facilitate the optimization of human-robot collaboration. Our findings indicate the influence of rest break duration on the recovery of human workers and offer strategies to reduce strenuousness during production planning involving cobots. This work contributes to creating a more efficient and ergonomic working environment for all parties involved, promoting human well-being and presence in the industrial workshop. By emphasizing the significance of considering physical strain and rest breaks as essential factors in the 5.0 factory, we pave the way for improved human-robot interaction and performance in manufacturing settings.

Index Terms—Rest break, Strenuousness, Cobots, Optimization

I. INTRODUCTION

Industry 5.0 is currently focused on re-establishing the human element at the core of the manufacturing system and prioritizing the well-being of individuals [1]. As a result, a re-evaluation of risk management, including factors such as fatigue risk and synchronisation of different components and services in the workshop, has become essential [2]. The workload of an agent is identified as one of the primary contributors to fatigue risk [3]. The Fatigue Risk Management System (FRMS) [3], derived from the Safety Management

System (SMS), incorporates considerations of the impact of fatigue on work. A previous work [4] models the workshop as an environment where the task must be scheduled over several machines in this representation of works, the Flexible Job-Shop Scheduling Problem (FJSP) provides a mathematical framework for task allocation across different machines while adhering to a set of constraints. Although the FJSP model has been used primarily to optimize production costs [5], it has also been used to address the physical strain experienced by operators [6]. The proposed scheduling aims to alleviate the physical strain on assembly line operators and optimize either the makespan or costs. Due to the scheduling's inherent precedence constraints, human workers frequently experience waiting periods during the production process. These waiting times are usually not long enough to restore the operators' energy levels, and they can prevent them from doing another task in a different process.

This study aims to regulate specific waiting times and their duration. We propose a tool that optimizes work schedules by maximizing rest break duration's for human agents and effectively managing strenuousness based on their physical workload, the impact on hardship is assessed with regard to the minimization of fatigue induces by maximized rest breaks duration's.

This paper is organized as follows: Section II provides a brief overview of the current state of the art in fatigue modeling and the impact of rest breaks on fatigue. Section III presents our approach. Section IV presents the obtained results and includes a discussion. Section V ends this paper with a conclusion and a set of perspectives.

II. STATE OF THE ART

In terms of management of injury risk and production issues, fatigue as been recognized as an essential element [7]. In [8] it has been observed that worker fatigue is linked to a progressive decline in quality over time, moreover the bad effects of fatigue not only affect the product quality but also reduce the well being of workers as shown in [9]. As a result, this decline leads to an elevated rate of defects in the production system. In [10] it is emphasized that prolonged

fatigue can contribute to an increased occurrence of human errors, which subsequently leads to a deterioration in product quality. According to [4], one of the primary causes of fatigue is the work schedule itself. Designing task planning and allocation based on ergonomic standards can help mitigate errors, accidents, and health problems [4]. Rest breaks form an integral part of ergonomic design, and effectively managing them can contribute to the prevention of musculoskeletal disorders. The implementation of rest break could allow an improvement of task performance as shown in [11] where the makespan has been reduced with an increasing of quality and quantity of products. Several studies has shown that short rest breaks over the working days are beneficial for tasks performance and can compensate for a loss of productive working [12]. Recovery periods could be organized in the work shift (internal recovery) or between work shifts (external recovery) [13]. The optimal time for a rest break for internal recovery is defined between three and ten minutes according to [14].

In this study we identified several methods for fatigue modelling as shown in table I.

TABLE I: References on Fatigue Quantification.

Reference	Model	Parameters
[15]	$F_s(t_i) = 1 - \exp(-\theta_i t_i)$	$F_s(t_i)$ is the fatigue accumulated by time t_i ; θ_i is the fatigue growth parameter when a worker completes a task i during time t_i .
[16]	$F_{i_{\max}} = MLC \cdot f_i \cdot MET_i$	$F_{i_{\max}}$ is the maximum fatigue index for task i ; MLC is maximum load capability; MET_i represents the maximum endurance time for task i individual's maximum capability;
[17]	$F(t) = 1 - \exp(-\lambda t)$	$F(t)$ is the fatigue accumulated by time t ; λ is the fatigue parameter.
[18]	$F_{jt} = 1 - \exp(-\theta_j t)$	F_{jt} is the percentage of maximum fatigue developed by the injured operator; θ_j is the workload level at the workplace.
[19]	$F_i = \frac{f_i}{MET_i}$	F_i denotes fatigue contribution per task i , and MET_i denotes maximum endurance time for task i .
[20]	$x_{i,j} = x_{i,0} e^{T \sum_{n=1}^{k_{i,j}} k_{i,j}}$	$x_{i,j}$ represents the fatigue state of the i -th person during the j -th interval of length T , and $k_{i,j}$ is the fatigue coefficient.

The rest breaks could be structured as shown in II

TABLE II: References on Recovery Quantification

Reference	Model	Parameters
[17]	$R(\tau_i) = F(t) e^{-\mu \tau_i}$	$F(t)$ tracks the total fatigue accumulated until a given time t , while $R(\tau_i)$ represents the residual fatigue after a rest period of duration τ_i ($\tau_i \geq 0$). The recovery parameter μ governs the rate at which fatigue is restored.
[21]	$RA = F_{tw} e^{-\mu \tau}$	F_{tw} represents the accumulated fatigue over time; tw denotes the duration of the working activity; τ represents the recovery time required for the operator to recover from the accumulated fatigue; μ is a physiological factor that alleviates the recovery process.

The authors [15] and [18] proposed studies utilize exponential functions to model excessive fatigue associated with work. These studies incorporate additional factors such as

workload variation, machine-related tasks, and dynamic activities in the packaging process to enhance the accuracy of fatigue estimation models. In [16] a model that assumes linear fatigue progression over time is presented. This model is adjusted using new data and takes into account operator fatigue when designing dual-resource constrained systems. Similarly, in [17], research works focus on muscular fatigue associated with sustaining a particular posture or force level required for a task. They propose an exponential increase in fatigue over time based on the muscle's Maximum Voluntary Contraction (MVC). In [19], a comprehensive approach incorporating discrete event simulation (DES), bio-mechanical analysis, and static fatigue models is employed to estimate fatigue rates. This methodology enables designers to assess the ergonomic implications associated with various system design alternatives. In [20], researchers have proposed an exponential model to characterize fatigue levels specifically in air traffic controllers. Their findings emphasize the faster accumulation of fatigue in states of heightened exhaustion.

The studies have identified three primary approaches to defining rest scenarios. These include varying the number of breaks in the production process, for example, in [15] a rest break between jobs is planned if the level of fatigue exceeds a certain threshold or in [22] optimizing rest break effects by adjusting break length, or combining both methods.

The methods including a fatigue parameter such as [17] and [15] are well suited regarding to the FJSP model developed with a strenuousness fatigue. As we consider the fatigue can be modelled as an exponential law the rest should also been considerate as exponential as in the works of [21], we also consider that the recuperation speed is slower than the fatigue growth (half as fast).

Fatigue has also been extensively studied in the context of the Flexible Job Shop Scheduling Problem (FJSP). In [23], a comprehensive analysis of a fatigue-conscious dual-resource-constrained FJSP is presented. The authors proposed an innovative approach that utilizes exponential functions to model both fatigue and rest periods. This model takes into account the strenuousness of fatigue and assumes that fatigue and rest follow an exponential pattern. The study conducted in [23] exemplifies the efficacy of incorporating fatigue-awareness in FJSP models using the exponential fatigue and rest framework. Their approach is solved using an enhanced version of the Non-dominated Sorting Genetic Algorithm II (NSGA-II). By integrating fatigue modeling into the scheduling problem, their methodology allows for a more realistic representation of operator well-being and performance during job shop operations. In [24], the Dynamic Flexible Job Shop Scheduling Problem under Worker Fatigue Constraint (DFJSP-WF) is addressed using the NSGA-II algorithm. They considered worker fatigue as a constraint, leading to tardiness in the production process. Their dynamic approach accounts for job cancellation, new job arrivals, and machine breakdown, ensuring efficient scheduling in real-world production settings while prioritizing worker well-being and minimizing tardiness. In [25], the authors solve the Dual Resource Constrained Flexible Flow Shop Scheduling

Problem (DRC-FFSP) using a Mixed-Integer Programming (MIP) model. They aim to minimize makespan while considering constraints related to machines and heterogeneous human workers with varying skills and characteristics. To achieve efficient scheduling solutions, they propose two paradigms of a Hybrid Metaheuristic Algorithm (HMA).

Compared to other methods, our proposed model offers several key advantages. Firstly, its implementation is easier due to the use of a Mixed-Integer Linear Programming (MILP) formulation, which simplifies setup and solution compared to evolutionary algorithms like NSGA-II. Additionally, our model's offline fatigue calculation enhances efficiency and adaptability in scheduling scenarios. Moreover, the custom definition of strenuousness levels using a generalizable approach allows us to accurately capture individualized fatigue behavior, providing a realistic representation of operator well-being and performance [26]. Overall, our model presents a compelling solution for the Flexible Job Shop Scheduling Problem, combining ease of implementation, computational efficiency, and accurate fatigue modeling to optimize scheduling outcomes and promote worker health and productivity. Importantly, our model achieves these benefits without increasing the makespan, as it effectively decreases the fatigue level and improves the well-being of human agents.

III. PROBLEM STATEMENT

In this research paper, we focus on optimizing waiting times for human agents in the FJSP model. Production planning involving cobots sometimes results in waiting times for human agents due to resource allocation and precedence logic between operations. To achieve this, we propose a two-step approach. Firstly, we utilize the Gurobi solver [27] to find an initial solution for the scheduling problem. The Gurobi solver helps us efficiently determine an optimized schedule, minimizing the waiting times for human agents. The second step involves a manual analysis. In this step, we apply the "law of fatigue and rest" to the schedule obtained from the optimization process.

The waiting times are induced by the precedence constraints existing in the FJSP, these times are often too short for consider resting for the agent [14]. In this research work we tried to organize the waiting time in order to obtain the better profit in terms of recuperation, the impact of operation's scheduling order and duration is analyzed. An extension of the model formulated by Özgüven & al [28] is proposed.

This section presents our research work as an expansion of the classical FJSP Problem. We focus on a set of jobs denoted as $\mathcal{I} = 1, \dots, i, \dots, I$. These jobs can be processed using a collection of m machines represented by $M = \{m_r\}_{r=1}^m$. Within this machine set, there are three types: Human agents (denoted as $r = Ha$), Robot agents ($r = Ra$), and Collaborative agents where humans and robots work together ($r = Co$).

In our model, both the robot and human agents have the option to work independently or collaborate to complete a job. Each job, denoted by i , is considered complete when all its constituent operations, denoted as I_{j1}, \dots, I_{jl_j} , are finished.

The operation j of job i can be processed by any available resource and has a specific processing time denoted as $pt_{j,i,r}$.

The assumptions underlying the classical FJSP can be stated as follows:

- 1) The processing times of operations are known and remain constant.
- 2) Setup times, which refer to the time required to prepare a machine for processing different operation, are not taken into account.
- 3) Transportation times, involving the movement of jobs or resources between machines, are not considered.
- 4) All jobs are available and ready for processing at the beginning (time 0).
- 5) Pre-emption, which refers to interrupting the processing of an operation to accommodate another, is not allowed. Each machine can handle only one operation at a time.
- 6) There exists a unique and feasible plan for each job, implying that there is only one valid sequence of operations for job completion.

The variables and parameters of our study's model are extended from the works of [28] and presented in Table. III and Table IV, respectively.

TABLE III: Decision variables

Variables	Definition
$X_{j,i,r}$	1 if the operation j of task i is realized by the resource r . 0 otherwise.
$P_{j,i,j',i',r}$	1 If the operation j', i' precedes the operation j, i . 0 Otherwise.
C_{max}	The maximum completion time over all jobs (Makespan).
H_{max}	Maximum hard working level.
$idle$	The period of time between operations for an agent.
$C_{j,i,r}$	Completion time of operation j of task i on machine r .
$S_{j,i,r}$	Starting time of operation j of task i on machine r .
C_{j_i}	Completion time of task i .

TABLE IV: Parameters

Parameters	Definition
$dP_{j,i,j',i'}$	1 if the operation $O_{j,i}$ precedes the operation $O_{j',i'}$. 0 otherwise.
$pt_{j,i,Ha}$	Processing time for the human agent.
$pt_{j,i,Ra}$	Processing time for the robot agent.
$pt_{j,i,Co}$	Processing time for collaborative task.
$H_{j,i,Ha}$	Hard working level of operation j of task i for human.
$H_{j,i,Ra}$	Hard working level of operation j of task i for cobot.
$H_{j,i,Co}$	Hard working level of operation j of task i for both agents.
α	Modulates C_{max} and $idle$ importance ($\alpha \in [0, 1] \subset \mathbb{R}$).
M	A large number.
\mathcal{T}	Strenuousness maximum level authorized.

Objective functions:

The multi-objective approach aims to minimize both the makespan (f_1) and waiting times (f_2) between operations. By utilizing the lexicographic method (*lexMin*) [1], the optimization process first focuses on minimizing the makespan and then prioritizes reducing waiting times. This approach ensures longer rest breaks instead of multiple short waiting periods, resulting in improved scheduling efficiency.

During the evolution of α , two transitions were observed that led to an increase in the number of collaborative operations. Among these transitions, two situations stand out as strong candidates: α values of 0.3 and 0.5.

IV. RESULTS AND DISCUSSION

In a scenario involving agents with heterogeneous capacity such as human and cobot, working alone or together to the completion of a job, the constraints are inducing waiting time for agents. If they are not affecting the robotic agent, these waiting times impact human agents by adding fatigue and hardship caused by waiting time. By studying these waiting times we observed that a first optimization without regulation for break length generate erratic behaviors for scheduling of the operations subject to precedence constraints as shown in Figure 1.

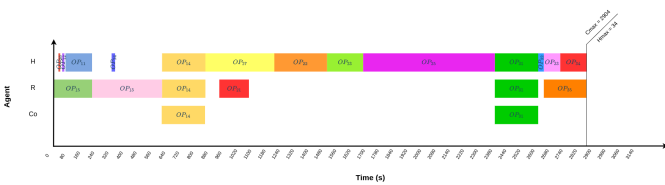


Fig. 1: Gantt diagram before optimization of waiting times

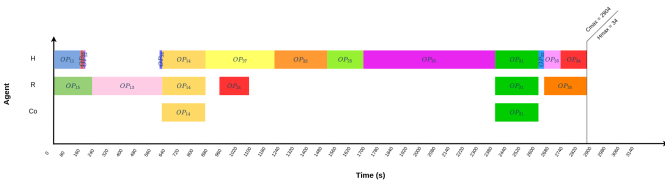


Fig. 2: Gantt diagram after optimization of waiting times

In order to extend rest break durations, the minimization of idle time in Equation (2) was used to reschedule operations. Initially, there were four breaks with durations of 0.11, 0.11, 3.81, and 2.45 minutes (Figure 1). After optimization, these breaks were consolidated into a single break of 6.86 minutes (Figure 2). Breaks with durations less than three minutes are not considered rest breaks, as mentioned in [13]. These short waiting times can lead to supplementary strenuousness because the human worker is unable to do anything else but wait. The exponential nature of fatigue and recovery laws means that longer durations result in lower fatigue indices.

Figure 3 and figure 4 illustrates the reduction in fatigue over time for two scenarios: before and after optimization, considering collaborative tasks. The new set of constraints and objectives allows a reduction in fatigue, approximately 2.5% and 4.5% lower, respectively. Importantly, this reduction was achieved without changing the order of operations, but by adjusting their scheduling to minimize idle time between them.

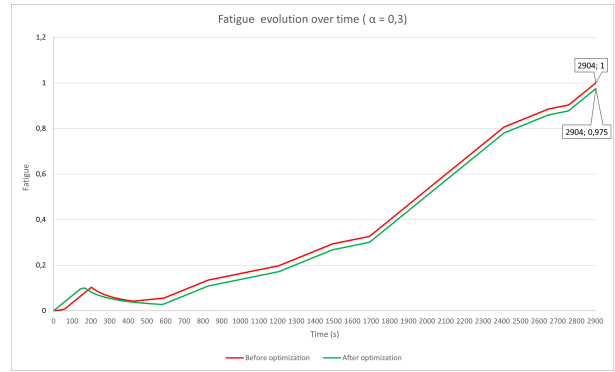


Fig. 3: Evolution of the fatigue over time before and after optimization $\alpha = 0.3$

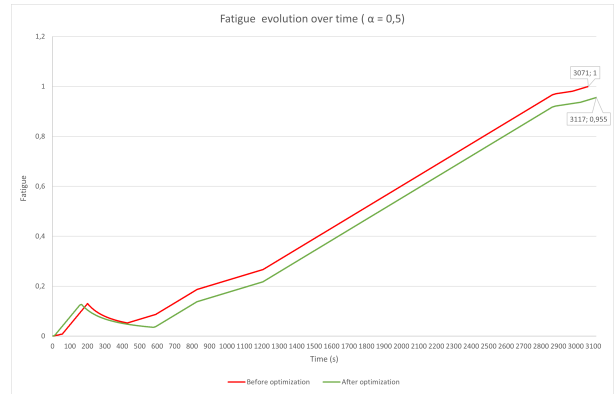


Fig. 4: Evolution of the fatigue over time before and after optimization $\alpha = 0.5$

While optimizing the scheduling process and reducing fatigue for human operators is crucial, it is equally vital to address the ethical implications of integrating collaborative robots (cobots) into the workplace. The increasing adoption of cobots may lead to concerns about job displacement, as workers may worry that automation will replace certain tasks, resulting in potential job losses. Therefore, it is imperative to implement cobots in a manner that complements human abilities and enhances overall productivity without replacing human workers.

Optimizing rest breaks and scheduling not only improves ergonomics and reduces fatigue for human agents but also promotes their overall well-being in the workplace. Minimizing strenuousness and providing adequate rest can lead to higher job satisfaction and better mental health among workers. Moreover, implementing collaborative robots in a manner that prioritizes human well-being fosters increased acceptance of cobots by human operators. By ensuring a fair distribution of tasks based on the custom strenuousness index, our model enhances job satisfaction and supports a harmonious human-robot collaboration in the production process.

V. CONCLUSION

In this research, we have examined how rest breaks impact the level of strenuousness. Through the integration of con-

straints and the utilization of a lexicographic multi-objective modeling approach, we have successfully minimized fatigue while preserving the original makespan. Our findings underscore the importance of considering the unique characteristics of each operation during scheduling, rather than solely focusing on their sequence, to optimize the ergonomic design of the process.

This study revolves around analyzing a real case of scheduling in an industrial workshop, subject to a comprehensive evaluation in real working conditions. The main focus is on enhancing the ergonomics of human-robot collaboration and the planning process, with the ultimate goal of increasing the acceptance of collaborative robots (cobots) by human operators and the well-being of human agent itself. Although mathematical modeling provides satisfying results, to effectively measure the impact of these improvements, the process will need to be implemented using the new model considering rest breaks duration maximization in order to observe the assessment of rest breaks on strenuousness, allowing for a direct comparison with the previous model. Notably, operator feedback will play a pivotal role in the later stages of the study, providing valuable insights into the scheduling process and ultimately aiming to foster improved acceptance of cobots in the production process while enhancing the well-being of human agents.

Moving forward, it would be advantageous to explore predictive models for determining rest break requirements to avoid surpassing pre-established fatigue thresholds. Additionally, dynamically adjusting the difficulty level based on the order of operations could offer a more ergonomic scheduling approach.

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