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Optimized Production Plan Under Ergonomic Aspects and Operational Effectiveness

O. El Mabrouk^{1,2}, M.A Kammoun¹, Z. Hajej¹, A. Chaker², S. Bennour²

¹Computer Production and Maintenance Laboratory (LGIPM), Lorraine University, Metz, France

²Mechanical Laboratory of Sousse (LMS), ENISO, University of Sousse, Tunisia
(oumayma.elmabrouk@eniso.u-sousse.tn)

Abstract - The well-being of operators plays a key role in enhancing efficiency, productivity, and demand fulfillment in manufacturing systems. Improving both ergonomic conditions and operational effectiveness is essential for cost optimization, taking in account inventory cost, while meeting demand. This paper explores the integration of ergonomic considerations with production strategies. Recognizing the interconnectedness of these factors, we propose practical solutions to enhance system performance while safeguarding operator health. A model is developed incorporating inputs from ergonomic metrics, production process and production demand. Thus, the total production cost was optimized under the predefined constraints to balance productivity and worker well-being while meeting production targets within service level agreements. The results of our model demonstrate the effectiveness of our ergonomic strategy in optimizing production plans, which enhances production output and reduces costs while balancing the workload for operators.

Keywords - Industry 5.0, Production planning, Ergonomic Aspect, Optimization, Rotation Strategy

I. INTRODUCTION

In today's rapidly evolving manufacturing landscape, Industry 5.0 represents a cutting-edge approach that seamlessly blends human expertise with advanced technology. This new paradigm goes beyond simple automation, emphasizing a collaborative relationship between humans and machines to boost productivity and drive innovation to new heights [1]. At the core of Industry 5.0 also known as "Human-Centric Industry", lies a profound appreciation for ergonomic principles [2] and supply chain efficiency [3], recognizing them as vital components in shaping the future of production. In this context, understanding the foundational elements that Industry 5.0 seeks to enhance and integrate is important. In manufacturing systems, ergonomic considerations are essential due to their direct influence on operators' capabilities and well-being, thereby affecting productivity [4]. Moreover, supply chain efficiency is paramount to the overall operational effectiveness of the system. Optimizing both ergonomic factors and production efficiency is essential for enhancing production performance, which substantially impacts revenues and profitability. The growing need for comprehensive production optimization strategies [5] that address these challenges, ergonomic aspects, and production efficiency,

underscores the importance of a thorough review of existing literature in the relevant research fields.

Researchers have developed a variety of ergonomic interventions to enhance human factors in manufacturing systems; divided into two primary types; Engineering controls and administrative controls interventions [6-7]. For instance, a previous study used an enhanced genetic algorithm to optimize job rotation, resulting in improved ergonomic conditions for 69% of workers [8]. Other works have explored worker assignment and job rotation considering ergonomic criteria and workforce scheduling by using sequencing generalized assignment formulation [9-15-16]. Ergonomics is a key factor for better performance by enhancing worker productivity.

However, other researchers focus on critical aspects related to supply chain optimization, including demand variance. Numerous methods have been developed to address this issue. A previous study focuses on understanding demand variances, while others recommend strategies like order batching, considering order trends, and information sharing to mitigate the bullwhip effect and reduce costs [10-17]. Additionally, there has been a significant focus on leveraging advanced technologies to enhance quality management within supply chains [11].

Previous research has often examined ergonomic concerns and supply chain dynamics separately. However, there is a growing recognition of their interconnected nature. As managers prioritize supply chain efficiency to meet tight deadlines, it can inadvertently increase the musculoskeletal disorders (MSDs) risks for operators. Hence, a holistic approach is necessary, integrating ergonomic interventions with supply chain management to balance productivity and worker well-being. In this paper, we aim to explore this relationship further and propose practical solutions to enhance both system productivity and operator health, while ensuring that production targets are met within the service level agreements. We propose a rotation strategy, using an ergonomic multi-criteria evaluation, that integrates ergonomic aspects correlated to the production planning. This article will continue with this structure, Section II presents the methodology and notation, Section III details the mathematical model, Section IV showcases a numerical example demonstrating the approach's effectiveness, Section V discusses the results, and finally section VI for the conclusion.

II. METHODOLOGY AND NOTATION

A. Notation

H : Finite production horizon that is divided into T periods ($k = 1 \dots T$) with length Δ_k ;

δ_{p_k} : Length of sub-period p_k within period k with ($p_k = 1 \dots P$);

D_k : Random demand over period k that follows a normal distribution;

S_k : Inventory level at the end of period k ;

N_w : Total number of workers to be assigned ($j = 1 \dots N_w$);

L : Number of workstations in the studied production line ($i = 1 \dots L$);

F_{jp} : Total score of workloads to which operator j is exposed during period k ;

C_u : Unit manufacturing cost;

C_s : Unit inventory cost;

C_l : Unit shortage cost;

C_{PT} : Total production cost;

$U_{p_k}^j$: Produced quantity by an operator j at the end of the sub-period p_k ;

B. Problem Statement

The studied production line is composed by workstations arranged in series, each equipped with identical machines operating in parallel (see Fig.1). In every workstation, a single task is repeated across all production units, and each unit is operated by a multi-skilled operator that can be assigned to any workstation. The workstations operate sequentially to produce a final product to meet a stochastic demand at the end of a production period while guaranteeing a predefined service level. We assume that the production horizon is finite, and it is divided into T periods, ($k = 1 \dots T$) with length Δ_k . Furthermore, special consideration is given to the ergonomic factors of different workstations, an extensive ergonomic assessment is conducted to ensure that workers are not assigned to the same task for the entire production period; i.e. workload and risk factors vary from one workstation to another. This approach promotes task diversity and helps mitigate musculoskeletal disorders (MSDs) resulting from repetitive tasks involving uncomfortable postures. In this context, we introduce the concept of dividing the production period k into P sub-periods ($p_k = 1 \dots P$) . At the end of a sub-period, the rotation of operators between workstations is decided to balance the workload.

The relationship between man-machine operations, the total production cost, and the service satisfaction rate

depends on the capacity and performance of the workers. This observation motivated us to propose a new approach aimed at developing an economic production plan for the stations over a finite production horizon, meeting random demands while respecting the required service levels. This approach also emphasizes the ergonomic aspect by proposing an efficient rotation plan for operators between stations to balance the workload, reduce ergonomic risks, and prevent MSDs.

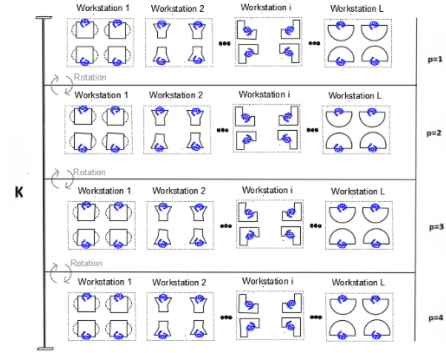


Fig. 1. Workstations with horizon production divided.

III. MATHEMATICAL MODEL

As stated, the proposed approach aims to develop a cost-effective production plan while enhancing operator well-being by reducing the risk of musculoskeletal disorders (MSDs). To achieve this, the model proposes rotating operators based on ergonomic evaluations of the workload associated with each workstation. In this section, a statistical methodology is first presented for calculating the workload of each workstation based on two ergonomic risk assessment methods. Subsequently, the optimization model is introduced.

A. Workload Assessment and Quantification

1) *Criteria evaluation*: Two ergonomic methods have been utilized to evaluate the degree of ergonomic risk which are the REBA (Rapid Entire Body Assessment) [12] and OCRA (Occupational Repetitive Actions) [13]. These two methods are complementary: REBA analyzes awkward body postures, while OCRA assesses task repetitiveness. Each provides a score that reflects the level of risk associated. As shown in (Fig. 2), the intervals of both methods were re-standardized to simplify the presentation of severity, resulting in three color-coded categories: Green, Yellow, and Red. Green indicates minimal workload and acceptable conditions, Yellow signifies moderate workload, and red denotes high workload situations. For every workstation task, data analysis from recordings, using IMU sensors and depth cameras can be made to classify the score of each studied criteria [14].

	REBA	OCRA
GREEN	1 - 3	7.5 - 11
YELLOW	4 - 7	11.1 - 14
RED	8 - 10	14.1 - 22.5

Fig. 2. Criteria evaluation.

2) *Workload quantification*: To quantify the green (G), yellow (Y), and red (R) scores, obtained from the ranges of REBA and OCRA methods into specific workload levels, we conduct a mathematical analysis. We denoted by:

SC_c : Score of criteria c , $c \in \{REBA, OCRA\}$;

$WL_{i,c}$: Workload level of criterion c in workstation i ;

Fig. 2 introduces the score intervals for both REBA and OCRA methods. This quantification aims to create a numerical value that reflects the overall workload level by combining the scores from both approaches, which range from 1 to 10 for REBA and from 7.5 to 22.5 for OCRA. To achieve this, the obtained scores are normalized to fall between 0 and 1, as described in equation (1) for both criteria.

$$\text{Score standardization: } \begin{cases} WL_{i,REBA} = \frac{SC_{REBA} - 1}{10 - 1} \\ WL_{i,OCRA} = \frac{SC_{OCRA} - 7.5}{22.5 - 7.5} \end{cases} \quad (1)$$

The global workload WL_i , is determined by considering the most severe workload between $WL_{i,REBA}$ and $WL_{i,OCRA}$, as expressed by equation (2).

$$WL_i = \text{Max}(WL_{i,REBA}, WL_{i,OCRA}) \quad (2)$$

The overall classification of workstations is presented in the following equations.

$$\begin{cases} \text{if} & 0 \leq WL_i \leq 0.23 \rightarrow G \\ \text{elseif} & 0.24 \leq WL_i \leq 0.66 \rightarrow Y \\ \text{else} & 0.67 \leq WL_i \leq 1 \rightarrow R \end{cases} \quad (3)$$

B. Optimization Model

The proposed approach aims to minimize the total production cost, as formulated in our objective function (4) while integrating the impact of operator capacity related to workload exposure F_{jp_k} . In addition, the production cost includes the inventory and shortage costs.

$$C_{PT} = C_u \cdot \sum_{k=1}^T \sum_{p_k=1}^P \sum_{j=1}^{N_w} U_{p_k}^j \cdot e^{-F_{jp_k}} + \left(C_s \cdot \sum_{k=1}^T S_k \cdot 1_{S_k > 0} \right) + \left(C_r \cdot \sum_{k=1}^T |S_k| \cdot 1_{S_k < 0} \right) \quad (4)$$

With:

$1_{S_k > 0}$ equals to 1 if $S_k > 0$ and equal to zero otherwise;

$1_{S_k < 0}$ equals to 1 if $S_k < 0$ and equal to zero otherwise

• Ergonomic Constraints

The workload score F_{jp_k} is computed by equation (5), which is in function of the global workload WL_i and the operator characterization score Q_j .

$$F_{jp_k} = WL_i \cdot X_{ijp_k} \cdot Q_j \quad (5)$$

X_{ijp_k} equals to 1 if operator j is assigned to the workstation i during sub-period p_k , and 0 otherwise.

The constraint given by equation (6) guarantees that each operator in every sub-period is assigned to exactly one workstation.

$$\sum_{i=1}^L X_{ijp_k} = 1 \quad \forall j \in \{1, \dots, N_w\}, p_k \in \{1, \dots, P\} \quad (6)$$

To classify the global workload as high, moderate, or acceptable, three binary variables are defined. A_{jp_k} , B_{jp_k} and C_{jp_k} equal 1 if the operator is assigned to a workstation with a high, moderate, or acceptable global workload, respectively. Constraint (7) establishes the global workload, and constraint (8) ensures that the operator is exposed to only one workload type (acceptable, moderate, or high) during a given sub-period.

$$WL_i \cdot X_{ijp_k} = WL_i \cdot C_{jp_k} + WL_i \cdot B_{jp_k} + WL_i \cdot A_{jp_k} \quad (7)$$

$$C_{jp_k} + B_{jp_k} + A_{jp_k} = 1 \quad (8)$$

The rotation of operators between workstations is subject to an ergonomic constraint modeled by the inequality (9), which ensures that an operator cannot be assigned to two consecutive high workloads. It assumed that after a high workload, an operator will be assigned to a moderate workload or a low workload. This rule helps balance the operators' workloads over a finite work horizon, consequently reducing ergonomic risks.

$$A_{jp_k} - B_{jp_{k+1}} - C_{jp_{k+1}} \leq 0 \quad (9)$$

• Production Constraints

Equation (10) represents the quantity transferred from the workstation to workstation $i+1$. The inventory level is calculated as a function of the produced quantity and the random demand, as formulated by equation (11). To ensure that production meets the demand in all periods, the service level constraint is added, as formulated in equation (12). The upper and lower limits of production for each operator during a sub-period are defined by equation (13).

$$\sum_{j=1}^{N_W} U_{P_k}^j \cdot X_{ijp_k} \cdot e^{-F_{jp_k}} \geq \quad (10)$$

$$\sum_{j=1}^{N_W} U_{P_k}^j \cdot X_{(i+1)j(p_k+1)} \cdot e^{-F_{j(p_k+1)}} \forall i \in \{1, \dots, L-1\}$$

$$S_k = S_{k-1} + \sum_{j=1}^{N_W} U_{P_k}^j \cdot X_{Ljp_k} \cdot e^{-F_{jp_k}} - D_k \quad (11)$$

$$\text{Prob}[S_k \geq 0] \geq \theta \quad (12)$$

$$U_{\min} \leq U_{P_k}^j \leq U_{\max} \quad (13)$$

IV. NUMERICAL APPLICATION

The production system consists of three workstations with 3, 2, and 2 operators. The production horizon is 2 months, and it is divided into 8 periods: $T = 8$, each Δ_k equivalent to one week. Also, each period is divided into 3 sub-periods with length $\delta_k = 13.33$ hours. We assume the following input data: $C_u = 10m.u.$, $\theta = 0.8$, $U_{\min} = 43$ and $U_{\max} = 56$; $C_s = 2.5m.u.$, $C_l = 8m.u.$, $S_{\min} = 0$ and $S_{\max} = 20$.

- **Calculation of workstation workloads and operator characterization scores**

We employ equation (1) to compute the workload based on OCRA and REBA criteria for the three workstations. Afterward, by applying equation (2), we find the global workloads for each station as follows: $WL_1 = 0.1$, $WL_2 = 0.44$ and $WL_3 = 0.88$. The obtained characterization score of operators is following:

$Q_1 = 1.5$, $Q_2 = 1.45$, $Q_3 = 1.55$, $Q_4 = 1.53$, $Q_5 = 1.49$, $Q_6 = 1.53$ and $Q_7 = 1.57$.

By solving the optimization problem presented in Section III, we obtain the optimal rotation plan and the economical production plan that satisfies the service level $\theta = 0.8$. The optimal rotation plan among the three workstations at the first production plan ($k=1$) is shown in TABLE I. As can be seen, the worker's assignment is changed from one sub-period to the next depending on the

workstation workload and the operator's characterization score.

TABLE I
OPTIMAL ROTATION PLAN OF THE FIRST PRODUCTION PERIOD

	Assignment sub-period 1	Assignment sub-period 2	Assignment sub-period 3
Workstation 1	4, 1, 3	2, 7, 5	2, 6, 7
Workstation 2	7, 6	4, 1	5, 3
Workstation 3	5, 2	3, 6	1, 4

- **Optimal production plan**

To illustrate the effectiveness of our approach, we propose two production strategies for the 8 periods: one with ergonomic considerations and one without. The results of these strategies are presented in Fig. 3. The production plan and storage level related to the optimal rotation, like the example in Table I, are presented by the curves labeled Production 2 and Stock 2, respectively. For the same random demand, we can notice a reduction in the occurrence of shortages from four times ($k=2$, $k=4$, $k=7$, $k=8$) to only two times ($k=6$, $k=7$). This reduction in the number of shortages is supported by a decrease in the quantity in shortage, from 29 to 10 lacking items; considering the maximum quantity in shortage for both strategies.

Based on Equation (4), The total cost obtained with the first strategy, amounts to $C_{PT} = 26612mu$. Taking into account ergonomic considerations, the calculated cost become $C_{PT} = 26507mu$. In addition to optimizing costs, the workload distribution among operators has become balanced, which guarantees a reduction in MSD. To show the balance effect we calculated the cumulative ergonomic score of the rotation plan presented in TABLE I, we calculated $(F_{j1} + F_{j2} + F_{j3})$ for each operator, then we compared the highest score to the lowest. We found the difference between them to be 0.98, which equals 3.36 without applying the rotation strategy.

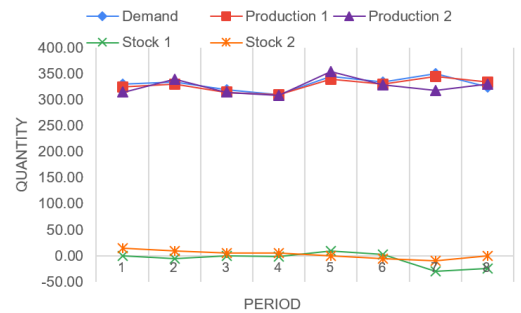


Fig. 1. Production strategies before and after rotation.

V. DISCUSSION

The results of our study highlight the effectiveness of

our combined cost and ergonomic based strategy in optimizing production plans. Implementing the presented strategy, reduced the total cost by $105m.u$, while respecting a service level $\theta = 0.8$.

Key benefits include increased production efficiency and reduced inventory shortages. By effectively balancing workload through rotation among operators, the strategy enhances overall productivity and results in a more efficient production process with lower operational costs. This demonstrates the significant potential of ergonomic optimization in improving production performance and cost-effectiveness. In addition, considering ergonomics has a significant impact on the industrial world. It makes workers safer and lowers the risk of injuries and musculoskeletal disorders (MSDs).

VI. CONCLUSION

This paper presents a production plan that takes into account ergonomic considerations, consisting of a rotation strategy. First, we classified workstations based on their workloads and operators based on their individual factors by applying scientifically validated assessments. Second, we calculated the characterization score of each assigned operator to manipulate the rotation strategy based on it. To illustrate the importance of this approach, we employed an example comparing two production strategies. In the first strategy, no ergonomic considerations were applied. In the second, we implemented the ergonomic rotation approach.

The results showed that the proposed approach optimized storage levels at the end of the production period reduced total production costs, and balanced the overall workload on operators.

However, to further enhance the effectiveness of this strategy, a dynamic approach will be considered in future research to decide on the optimal timing for workstation rotations, rather than implementing them statistically at the end of each sub-period.

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