Heliyon 10 (2024) e31820

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Integrated operations planning model for the automotive wiring industry

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A R T I C L E I N F O

Keywords:
Production
Storage
Linear programming
Operational planning
Automotive wiring industry

A B S T R A C T

An integrated operations planning model for automotive wiring companies is studied to improve synchronization between production activities and inventory flows. These combined factors are growing in significance as they drive the need to take proactive steps in manufacturing and distributing wiring materials within the supply chain. This involves anticipating the requirements of different automotive manufacturers and thereby guaranteeing a consistent, uninterrupted, and punctual provision of raw wiring materials. This support is vital for sustaining the ongoing manufacturing operations in the automotive sector. For this push flow system, the proposed operational model is based on integer linear programming, considering capacity and bill of materials constraints to determine production quantities, inventory levels, and machine sizing. Real-life data from the automotive wiring industry validates the effectiveness of coordinated production and inventory activities, resulting in significant lead time reductions of up to 60 %. These findings provide compelling reasons for automotive wiring partners to engage in joint operations planning.

1. Introduction

Integrated operations planning has garnered significant attention from researchers in the industrial field in recent years. The reason for this focus stems from the need for companies to effectively manage their resources and optimize their activities to address market competition, ensure a steady and timely supply of products, and satisfy customers' requirements within shorter lead times. Achieving these goals necessitates the integration of procurement, production, and inventory decisions, which in turn requires close coordination among supply chain actors [1–3].

This coordination is particularly crucial in sectors where products have a significant impact on safety, efficiency, and quality across all aspects of the supply chain, especially in the face of intense global market competition. The automotive wiring industry is no exception to these challenges [4–6].

The automotive wiring industry faces, on the one hand, significant challenges due to the high volume and variety of products,

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https://doi.org/10.1016/j.heliyon.2024.e31820
Received 30 January 2024; Received in revised form 2 May 2024; Accepted 22 May 2024
Available online 23 May 2024
2405-8440/

coupled with limited production and storage capacities and Bill of Materials (BOM) constraints. On the other hand, the related production process encompasses several phases (Fig. 1) that necessitate the coordination of activities to maintain a seamless supply of raw materials and accommodate the personalized requirements of clients.

To overcome these challenges and ensure consistency across different production levels, close coordination between procurement, production, and inventory activities is crucial. This coordination enables a smooth transformation of articles into final products delivered to customers and optimizes industrial performance by establishing connections between the upstream level (article availability) and the downstream level (final products).

According to the high importance of wire drawing and toroning in the production of automotive wiring, the research will mainly focus on these two critical stages.

Wire Drawing involves creating the base wires from raw metal, while toroning involves twisting individual wires together to form stranded conductors. These processes significantly impact the performance, flexibility, and durability of the final product and they represent the basic steps to generate the raw material for the automotive industry. The considered company specializes in manufacturing diverse types of automotive wiring, where wire drawing and toroning are the primary areas of expertise. Focusing on these critical stages allows them to offer highly customized and specialized solutions to meet the specific needs of their customers after that.

The literature on integrated operations planning problems is abundant as shown by Utama et al. [1]. Different variants of this problem have been investigated: some works involve a single-stage production with multiple products [7–12], while others consider a specific product [13–17]. Some other papers study the case of multi-stage production with single product [18,19] or multi-products [20–23].

Noticeably, many integrated operations planning models are sector-specific and have been especially devoted to perishable products such as pharmaceutical products [23], food [3,9,11,14,15], manufacturing [8,19,20], and the automotive industry [4–6].

Firstly, Mustapha et al. [5] and Gallego and Garcia [6] investigated mainly the Sales and operations planning problem and developed predictive models to increase automotive producer efficiency. Secondly, for Kumar et al. [4], a firm that produces engines for automotive manufacturers is considered and a model was developed integrating scheduling, inventory, and maintenance costs to be reduced.

Nevertheless, to the best of our knowledge, integrated operations planning that incorporates multi-stage production with multi-products and multi-period operational planning decisions in the automotive wiring supply chain has not been investigated. This research will be devoted to filling in this gap.

This study addresses a complex production-inventory planning problem in the global automotive wiring industry, which involves multiple periods, products, and production levels. The aim is to assess the value of integrated operations planning in this industry. A case-oriented approach is employed, starting with determining production quantities, inventory levels, and machine sizing for a complex multi-machine system in an automotive wiring industry. The objective is to maximize overall production while considering capacity and Bill of Materials (BOM) constraints and maintaining consistency between wire drawing and toroning production levels. The model determines the quantities of products and articles to be produced and stored, as well as the required number of machines to meet workstation demand.

The problem is mathematically formulated as an integer linear programming model, considering production capacity and Bill of Materials (BOM) constraints. The results demonstrate that the proposed approach can yield significant economic benefits. To assess its robustness and implications across different production scenarios, a systematic sensitivity analysis is conducted. The findings from these comprehensive performance studies provide evidence of the value and effectiveness of the proposed approach related to the considered real case study.

The remaining sections of the paper are structured as follows: Section 2 provides a literature review that discusses relevant studies and research related to the topic of integrated production-inventory planning, and Section 3 presents the proposed approach to address the problem of integrated production-inventory planning at the operational level. The approach outlines the methodology and strategies used to tackle the problem. In section 4, the problem is formulated using linear programming techniques, taking into account the specific constraints and objectives of the integrated production-inventory planning problem related to a real case study from the automotive wiring industry. Section 5 offers a detailed illustration of the obtained results for a specific activity related to the medium section articles, demonstrating how the proposed approach can be applied in practice. In Section 6, a sensitivity analysis is conducted to assess the robustness and implications of the proposed approach under various scenarios. This analysis provides insights into the performance and effectiveness of the approach. Finally, Section 7 concludes the paper by summarizing the main findings and contributions. It also discusses potential future directions and areas for further research in the field of integrated production-inventory planning.

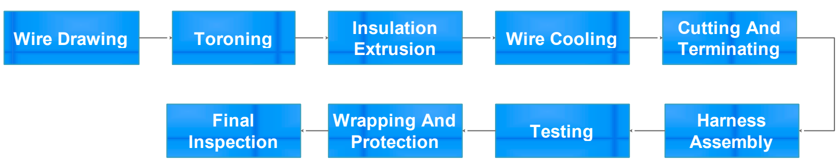

Fig. 1. Automotive wiring production process steps.

2. Literature review

The literature review section of the paper is divided into two subsections.

- the first one focuses on works that have investigated integrated production-inventory (IPI) planning. It provides an overview of studies that have addressed the integration of production and inventory decisions in various industries. It also discusses the main findings and contributions of these studies in terms of improving operational efficiency, reducing costs, and enhancing customer satisfaction.
- the second subsection is dedicated to automotive supply chain planning problems. It reviews the existing research on supply chain planning in the related field, with a specific focus on operations management. This subsection summarizes the main contributions of these studies in addressing the unique challenges and requirements of the automotive sector.

2.1. Integrated production-inventory (IPI) planning in the supply chain

On the one hand, some studies conducted by Utama et al. [1], Erenguc et al. [2] and Chen [3] have extensively explored the integrated production-inventory (IPI) planning problem. These studies have investigated various variants of the problem. Some works have focused on single-stage production with a single product and single material, as exemplified by the research conducted by Kumar et al. [13], Masudin et al. [14], and Fauza et al. [15], El-Baz and Taha [16] and Duan and Ventura [17]. Other studies have considered more complex scenarios involving multi-stage, multi-product, and/or multi-material settings, as demonstrated by the works of Fauza et al. [18], Utama et al. [19], Kaur et al. [20], Budiman and Rau [21], Nagar et al. [22] and Susarla and Karimi [23].

On the other hand, alternative methodologies have recently been investigated to address Integrated Production-Inventory Challenges by integrating Nature-Inspired Algorithms, AI, and Mathematical Optimization [24].

2.2. Single stage production

In the context of the integrated production-inventory (IPI) problem in single-stage production settings, several studies have been conducted focusing on a single-plant and single-product models. These studies have utilized integrated linear production-inventory models to formulate and address the problem.

Lo et al. [25] developed a cost minimization model that incorporates considerations of energy procurement and production scheduling with static time characteristics. Omar and Zulkipli [26] proposed a model that maximizes profit by optimizing a single vendor's procurement of raw materials from a single supplier, also taking into account static time characteristics. Duan and Ventura [17] developed a mixed integer linear programming model for dynamic supplier selection and inventory management in a serial supply chain. Their model considers a price break scheme and flexible periods.

For these studies, exact solution theories were established to solve the linear models, providing rigorous mathematical solutions. However, other authors have also developed heuristic procedures to tackle linear complex problems. Examples include the works of Kundu and Chakrabarti [27], Ben Daya et al. [28], Sana [29], and Mawandiya et al. [30].

These previous studies contribute to the understanding and optimization of single-stage production systems through the development of integrated linear models and solution approaches, encompassing factors such as energy procurement, production scheduling, profit maximization, supplier selection, and inventory management.

In addition to the integrated linear production-inventory models, several reviewed papers have also addressed the problem using non-linear production-inventory model considering the objective of profit maximization [3,14,15,31,32].

Indeed, the other reviewed articles that focus on the non-linear production and inventory model are primarily concerned with minimizing costs [9,13,16,33]. Shafiee et al. [9] addressed a single-stage production multi-product problem. Their non-linear model aimed to minimize costs while maximizing social impacts to design a real problem related to a dairy industry case study. Kumar et al. [13] developed a single-stage production model with fuzzy data and static time characteristics. El-Baz and Taha [16] proposed an integrated production-inventory model with controllable production rates and dynamic prices. Priyan et al. [33] considered a model that incorporated defective items. For all these studies, heuristic procedures are often used for problem solution.

2.3. Multi-stage production

In the other hand, some papers investigated the case of multi-stage production with single product [18,19] or multi-products [20–23].

Fauza et al. [18] considered a two-stage food production scenario with a single product and a single plant. Their model aimed to maximize profit and incorporated exponential perceived value loss. They utilized a genetic algorithms procedure to solve the non-linear formulated problem.

Utama et al. [19] focused on multi-stage production with a single plant, single product, and raw materials with static time characteristics. They developed a deterministic linear model with the objective of profit maximization. A two-stage production IPP mathematical model is proposed. The decision variables used are the frequency of raw material delivery, the frequency of delivery of finished products, and the production cycle time. The model developed aims to provide solutions to the inventory of raw materials, goods in process, and finished products. The Dragonfly Algorithm (DA) was used to solve the problem and find the optimized inventory decision variables.

Kaur et al. [20], and Budiman and Rau [21] presented stochastic models with dynamic time. While Nagar et al. [22] investigated multi-objective issues to optimize profit, service, and downside risk. Susarla and Karimi [23] investigated a multi-stage production, multi-plant, and multi-product problem in pharmaceutical companies. They proposed a dynamic mixed-integer linear model with the objective of cost minimization. An exact solution based on their proposed model was employed to solve the problem. These studies contribute to the understanding of the multi-stage production-inventory problem by considering factors such as static time characteristics, exponential perceived value loss, and multiple plants and products. They utilize linear or non-linear models and employ various solution approaches, including metaheuristics and exact methods.

2.4. New alternative methodologies

Embracing the complexity of Integrated Production-Inventory (IPI) challenges, a comprehensive approach emerges by amalgamating a spectrum of cutting-edge optimization algorithms. Drawing inspiration from nature, the Genghis Khan Shark Optimizer, Gazelle Optimization Algorithm [34], Geyser Inspired Algorithm [35], Prairie Dog Optimization Algorithm [36], and Dwarf Mongoose Optimization Algorithm [37] contribute adaptive and dynamic strategies, mimicking the efficiency observed in various natural systems. Incorporating the Lungs Performance-Based Optimization [38] brings a physiological dimension to the model, leveraging insights from respiratory efficiency. At the forefront of technological advancement, the Fake News Detection using Recurrent Neural Network based on Bidirectional LSTM and GloVe [39] offers a data-driven perspective, enhancing the robustness of decision-making processes. The mathematical sophistication of the A Sinh Cosh Optimizer [40] complements these nature-inspired and AI-driven approaches, adding a layer of precision to the integrated model. By unifying these diverse algorithms into a cohesive framework, this approach to tackling IPI problems navigates the intricate balance between production and inventory, showcasing adaptability, resilience, and a holistic understanding of the multifaceted challenges within the integrated production and inventory landscape.

2.5. IPI applied on automotive industry and main contribution of the present work

In the context of the automotive industry, Kumar et al. [4], Mustapha et al. [5] and Gallego and Garcia [6] stand out as studies that investigate the value of integrated operations planning.

Mustapha et al. [5] were interested in the tactical planning process that balances aggregate demand and capacities to deliver realistic production plans. They developed a multi-objective model to identify efficient aggregation schemes considering both sales and operations expectations. The model is implemented on numerical instances from automotive industry. The results highlight the existence of efficient and balanced aggregation schemes.

Gallego and Garcia [6] are also interested in sales and operations planning. They designed a generic predictive methodology to optimize sales and operations planning. This developed methodology combines demand scenarios, a statistical analysis of demand, forecasting techniques, random number generation, and system dynamics

For Kumar et al. [4], a firm that produces engines for automotive manufacturers is considered and a model was developed addressing multiple aspects of operations planning, including production scheduling, maintenance scheduling, and inventory control. They develop an integrated approach that encompasses job sequencing, batch-sizing, inventory levels, and preventive maintenance scheduling.

The proposed approach is assessed on a complex multi-machine system within the automotive industry, to minimize the Overall Operations Cost (OOC) calculated based on the sum of the scheduling cost, maintenance cost, and downtime inventory cost. The Objective function is non-linear and strongly NP-hard as it consists of various interdependent decision variables. The problem is subject to three constraints: demand satisfaction, job sequencing and batch size. A meta-heuristic namely, adaptive thermo-statistical simulated annealing algorithm is used to achieve near optimal solution in less computation time. The results demonstrate substantial economic improvements achieved through the integrated operations planning approach.

Despite the innovative methodologies, challenges persist in real-world implementation. These may include complexities in data integration, dynamic demand fluctuations, and the need for organizational alignment. Overcoming these hurdles is crucial for realizing the full potential of integrated operations planning methodologies in enhancing efficiency and competitiveness within the automotive sector.

Nevertheless, the specific problem of integrated production-inventory (IPI) planning, which incorporates multi-stage production with multi-products and multi-period operational planning decisions considering the bill of materials (BOM) real constraints in the automotive wiring supply chain has not been addressed in existing literature.

This research paper aims to bridge this existing gap by introducing an innovative approach centered around operational planning. Considering the distinctive characteristics and challenges inherent in the automotive wiring sector—including its intricate manufacturing processes and diverse product range—the proposed approach prioritizes the imperative coordination of procurement, production, and inventory functions. With the objective of offering tangible resolutions and valuable perspectives tailored to this industry, the proposed approach is designed to address practical challenges and provide actionable insights.

Through the integration of production and inventory planning, the aim of the study will be to optimize the key decisions such as production quantities, inventory levels, and machine sizing. By addressing these challenges, the expected result will contribute to the improvement of operational efficiency, cost-effectiveness, and customer satisfaction in the automotive wiring industry.

The proposed approach is tested using various production scenarios to study its robustness and implications. The results of such pervasive performance investigations confirm the value of the proposed approach over conventional approaches.

3. Proposed approach

The planning approach focuses on achieving operational-level integration of production and inventory activities. The limited capacity for both production and storage during multiple products manufacturing is taken into consideration. Unlike existing integrated models treated in the literature, which typically aim to minimize costs [41] or maximize profits [42], the current approach involves a conditional maximization of production according to inventory activities. Additionally, the required number of machines to process products is determined.

The proposed model focuses on two levels of production within the Metal zone: Toroning and Wire drawing. The Bill of Materials (BOM) constraints are also considered. Specifically, in the wire drawing area, production is based on rotating the production of articles of the same category on the same machine according to the article turnover rate and the stock level.

To clarify, if an article j1 reaches its maximum inventory level, its production is temporarily halted until the stock reaches a minimum level. During the production suspension period, the production of a new article j2 is initiated and the following steps should be tracked, in a cyclical manner, to decide about the new article to process.

- consider all articles in the same category
- classify articles according to the highest turnover rate
- then proceed to the production of the article with the lowest inventory level

In terms of production management in the toroning area, the objective is to maximize production using a similar approach, with the exception that there is no rotation of products involved. Additionally, this model enables us to determine the required number of stranding machines in this area.

Figs. 2 and 3 below illustrate the defined thresholds for production planning in the metal zone.

4. Problem's definition and formulation

4.1. Problem definition

This study deals with the optimization of industrial production in automotive wiring, focusing on a real case study of a specialized company in manufacturing electrical cables for the automotive sector. With a significant global presence established through advanced facilities in Portugal, Morocco, Romania, and Tunisia, the company operates two research and development centers and has established sales and technical support offices in Tunisia and Germany. Internal assessments are conducted to pinpoint operational inefficiencies. The latest study revealed notable issues in the metal processing zone, where a significant accumulation of work-in-progress stocks occurs in both metal production phases—wire drawing and toroning. This is attributed to inadequate planning of production and storage activities, as observed on-site.

The primary objective of this study is to improve the planning of production and storage activities by developing a system that facilitates the visualization of stock movements while adhering to production and storage capacity constraints. Thus, the central focus is on the company's internal production units, specifically the wire drawing and toroning areas. To tackle the complexities of the production process, a multi-level, multi-product, and multi-period model is considered.

The operational model, considering a weekly planning horizon with a daily periodicity, aims to maximize production while ensuring compliance with bill of materials (BOM) constraints.

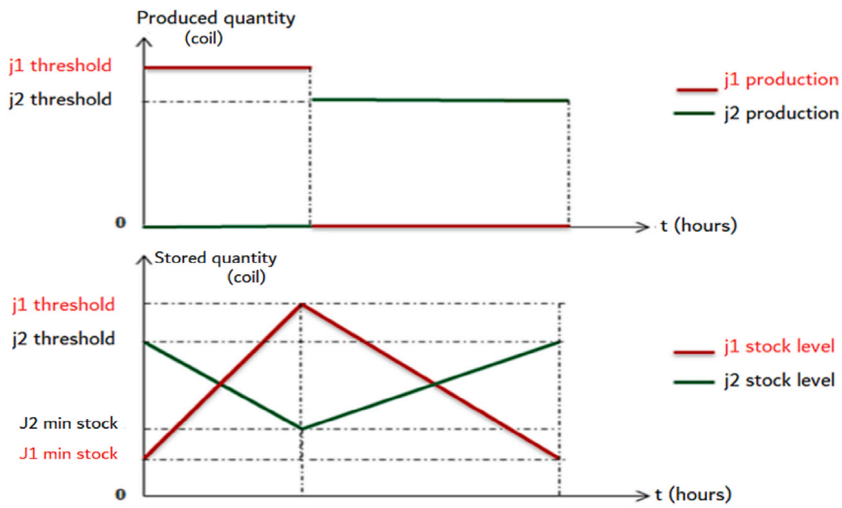

Fig. 2. Defined thresholds for production planning in the wire-drawing area.

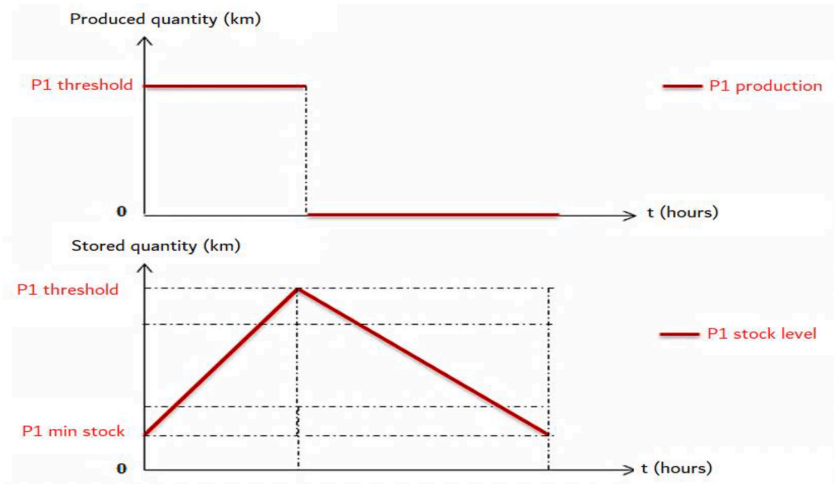

Fig. 3. Defined thresholds for production planning in the toroning area.

In addition to capacity constraints, the operational model also emphasizes maintaining consistency between the wire drawing and toroning production levels. This means that the decisions made by the model not only need to satisfy the capacity constraints of each production unit but also ensure that there is coherence and alignment between the two levels (wire drawing and toroning). This includes determining the appropriate quantities of products and articles to produce and store, as well as determining the required number of machines to meet the demand at each workstation.

By considering these factors and constraints, the operational model aims to generate feasible solutions that optimize production efficiency and meet the demand requirements of the company. By maximizing production while ensuring consistency and adherence to BOM constraints, the model can assist in decision-making and resource allocation, ultimately improving the overall performance of the production process.

4.2. Model formulation

4.2.1. Sets and indices

T: set of periods; $t \in T$.
P: set of products; $p \in P$.
A: set of articles; $J \in A$.

4.2.2. Storage settings

$Imax_p$: Maximum storage capacity of product p (expressed in km).
$Imin_p$: Minimum storage capacity of product p (expressed in km).
$Itremax_j$: Maximum storage capacity of article j (expressed in number of coils).
$Itremin_j$: Minimum storage capacity of article j (expressed in number of coils).
SIp_p: Initial inventory level of product p (expressed in km).
SIa_j: Initial inventory level of article j (expressed in number of coils).

4.2.3. Time and capacity settings

d_{pt}: demand for product p in period t (expressed in km)
C_{pj}: Product p compositions of article j
cap_p: Production capacity of product p (expressed in km)
$captre_j$: production capacity of Article j (expressed in number of coils)
ucs_j: Coil's capacity of article j (expressed in km)
$seuiltre_j$: Minimum threshold for article j production (expressed in number of coils)
$seuil_p$: Minimum threshold for product p production (expressed in km)
V_p : Average speed used for product p production
z: conversion factor.
Pas_p : The pitch value related to product p
RT: The objective value of the "Running time" performance indicator for product p production.
nohour: the number of hours worked per period t (expressed in hours)

4.2.4. Expressions

Required quantity of article j (expressed in number of coils):

$$BS_{jt} = \sum_{p \in P} \left(P_{pt} * \frac{C_{pj}}{\text{ucs}_j} \right)$$

Cpj refers to the types of article j used to manufacture the specific product P. By incorporating the composition of product P in the calculation of the required quantity of article j expressed in the number of coils, one can determine the exact quantity of each component needed to produce the specified product P, considering the capacity of a coil of article j.

Quantity of product p produced per hour (expressed in km):

$$prodheurtd_p = V_P * Pas_P * z$$

Where z is a conversion factor used to convert the result of the multiplication between the speed and the pitch into units of cable produced per hour. The pitch refers to the distance between the centers of two adjacent conductors within a cable harness.

Quantity of product p produced per workstation (expressed in km):

$$prodposte_p = prodheurtd_p * RT * nohour$$

4.2.5. Decision variables

$\mathbf{P}_{\mathrm{pt}}$: Quantity of product p produced during period t (expressed in km)
$\mathrm{Ptre}_{\mathrm{jt}}$: Quantity of article j produced during period t (expressed in number of coils)
$\mathrm{besoin}_{\mathrm{jt}}$: Quantity of article j needed to produce the product p during period t (expressed in number of coils)
$\mathbf{b}_{\mathrm{pt}}, \mathbf{a}_{\mathrm{jt}}$: Intermediate variables used in production management constraints
$\mathrm{nbTD}_{\mathrm{pt}}$: The number of machines needed to produce product p during period t
$\mathbf{I}_{\mathrm{pt}}$: Inventory level of product p at the end of period t (expressed in km)
$\mathrm{Itre}_{\mathrm{jt}}$: Inventory level of article j at the end of period t (expressed in number of coils)

4.2.6. Objective function

For the automotive industry, the goal is to proactively produce and push the wiring materials into the supply chain, anticipating the demand for various automotive manufacturers and suppliers. By implementing a push flow system, the automotive wiring production strives to ensure a steady and timely supply of raw materials to support the ongoing manufacturing processes.

That's why, it becomes necessary to maximize production and inventory levels as detailed in the objective function:

$$\text{Max} \left(\sum_{p \in P} \sum_{t \in T} \mathrm{P}_{\mathrm{Pt}} + \sum_{p \in P} \sum_{t \in T} \mathrm{I}_{\mathrm{pt}} + \sum_{j \in A} \sum_{t \in T} \mathrm{Ptre}_{\mathrm{jt}} + \sum_{j \in A} \sum_{t \in T} \mathrm{Itre}_{\mathrm{jt}} \right)$$

This objective function aims to maximize the production and the inventory of strands and of the drawn wire.

4.2.7. Constraints

4.2.7.1. Inventory activity constraints

$$\mathrm{I}_{\mathrm{p1}} = SIp_p + \mathrm{P}_{\mathrm{p1}} - d_{p1} \quad p \in P \tag{1}$$

$$\mathrm{I}_{\mathrm{pt+1}} = \mathrm{I}_{\mathrm{pt}} + \mathrm{P}_{\mathrm{pt+1}} - d_{pt+1} \quad p \in P\,;\ t \in T \tag{2}$$

$$\begin{cases} \mathrm{besoin}_{\mathrm{jt}} \geq BS_{jt} \\ BS_{jt} \geq \mathrm{besoin}_{\mathrm{jt}} - 1 + m\,; \end{cases} \quad j \in A;\ t \in T\,; m \text{ a very small number} \tag{3}$$

$$\mathrm{Itre}_{\mathrm{j1}} = SIa_j - \mathrm{besoin}_{\mathrm{j1}} \quad j \in A \tag{4}$$

$$\mathrm{Itre}_{\mathrm{jt+1}} = \mathrm{Itre}_{\mathrm{jt}} + \mathrm{Ptre}_{\mathrm{jt+1}} - \mathrm{besoin}_{\mathrm{jt+1}} \quad j \in A;\ t \in T \tag{5}$$

$$Imin_p \leq \mathrm{I}_{\mathrm{pt}} \leq Imax_p \quad p \in P;\ t \in T \tag{6}$$

$$Itremin_{jt} \leq \mathrm{Itre}_{\mathrm{jt}} \leq Itremax_{jt} \quad j \in A;\ t \in T \tag{7}$$

4.2.7.2. Production activity constraints

$$\mathrm{P}_{\mathrm{pt}} \leq cap_p \quad p \in P\,;\ t \in T \tag{8}$$

$$\mathrm{Ptre}_{\mathrm{jt}} \leq captre_j \quad j \in A\,;\ t \in T \tag{9}$$

$$\begin{cases} cap_p \geq Imax_p + d_{p1} - SIp_p \\ => \ \mathrm{b}_{\mathrm{p1}} = Imax_p + d_{p1} - SIp_p \\ cap_p \leq Imax_p + d_{p1} - SIp_p \\ => \ \mathrm{b}_{\mathrm{p1}} = cap_p \end{cases} \quad p \in P \tag{10}$$

$$\begin{cases} cap_p \geq Imax_p + d_{p\ t+1} - \mathrm{I}_{\mathrm{pt}} \\ => \ \mathrm{b}_{\mathrm{p\ t+1}} = Imax_p + d_{p\ t+1} - \mathrm{I}_{\mathrm{pt}} \\ cap_p \leq Imax_p + d_{pt+1} - \mathrm{I}_{\mathrm{pt}}\ t \in T \\ => \ \mathrm{b}_{\mathrm{pt+1}} = cap_p \end{cases} ; p \in P \tag{11}$$

$$\begin{cases} captre_j \geq Itremax_j + \mathrm{besoin}_{\mathrm{j1}} - SIa_j \\ => \ \mathrm{a}_{\mathrm{j1}} = Itremax_j + \mathrm{besoin}_{\mathrm{j\ 1}} - SIa_j \\ captre_j \leq Itremax_j + \mathrm{besoin}_{\mathrm{j\ 1}} - SIa_j\ j \in A \\ => \ \mathrm{a}_{\mathrm{j1}} = captre_j \end{cases} \tag{12}$$

$$\begin{cases} captre_j \geq Itremax_j + \mathrm{besoin}_{\mathrm{j\ t+1}} - \mathrm{Itre}_{\mathrm{jt}} \\ => \mathrm{a}_{\mathrm{jt}} = Itremax_j + \mathrm{besoin}_{\mathrm{j\ t+1}} - SIa_j\ j \in A\ ; t \in T \\ captre_j \leq Itremax_j + \mathrm{besoin}_{\mathrm{j\ 1}} - SIa_j \\ => \ \mathrm{a}_{\mathrm{j\ t+1}} = captre_j \end{cases} \tag{13}$$

$$\mathrm{P}_{\mathrm{pt}} \neq 0 => \begin{cases} \mathrm{P}_{\mathrm{pt}} = \mathrm{b}_{\mathrm{pt}} \\ \mathrm{P}_{\mathrm{pt}} \geq seuil_p \end{cases} \quad p \in P\ ;\ t \in T \tag{14}$$

$$\mathrm{Ptre}_{\mathrm{jt}} \neq 0 => \begin{cases} \mathrm{Ptre}_{\mathrm{jt}} = \mathrm{a}_{\mathrm{jt}} \\ \mathrm{Ptre}_{\mathrm{jt}} \geq seuiltre_j \end{cases} \quad j \in A\ ;\ t \in T \tag{15}$$

$$\begin{cases} \mathrm{P}_{\mathrm{pt}} = 0 \\ \mathrm{I}_{\mathrm{pt}} \geq d_{pt+1} + Imin_p \end{cases} => \mathrm{P}_{\mathrm{pt+1}} = 0 \quad p \in P\ ;\ t \in T \tag{16}$$

$$\begin{cases} \mathrm{Ptre}_{\mathrm{jt}} = 0 \\ \mathrm{Itre}_{\mathrm{jt}} \geq \mathrm{besoin}_{\mathrm{jt+1}} + Itremin_j \end{cases} \quad j \in A\ ;\ t \in T => \mathrm{Ptre}_{\mathrm{jt+1}} = 0 \tag{17}$$

$$\mathrm{P}_{\mathrm{pt}} \leq \mathrm{nbTD}_{\mathrm{pt}} * prodposte_p \quad p \in P\ ;\ t \in T \tag{18}$$

4.2.7.3. Restrictions on dependency links between articles j

$$\mathrm{Ptre}_{\mathrm{jt}} = 0 => \mathrm{Ptre}_{\mathrm{j+1\ t}} = 0 \quad j = 1\ ;\ t \in T \tag{19}$$

$$\mathrm{Ptre}_{\mathrm{jt}} \neq 0 => \mathrm{Ptre}_{\mathrm{j+2\ t}} = 0 \quad j = 1\ ;\ t \in T \tag{20}$$

$$\mathrm{Ptre}_{\mathrm{jt}} \neq 0 => \begin{cases} \mathrm{Ptre}_{\mathrm{j+1\ t}} = 0 \\ \mathrm{Ptre}_{\mathrm{j+2\ t}} = 0 \end{cases} \quad j = 4\ ;\ t \in T \tag{21}$$

$$\mathrm{Ptre}_{\mathrm{jt}} = 0 => \mathrm{Ptre}_{\mathrm{j+1\ t}} = 0 \quad j = 5\ ;\ t \in T \tag{22}$$

$$\mathrm{Ptre}_{\mathrm{jt}} \neq 0 => \mathrm{Ptre}_{\mathrm{j+1\ t}} = 0 \quad j = 7\ ;\ t \in T \tag{23}$$

4.2.7.4. Integrality constraints

$$\mathrm{P}_{\mathrm{pt}} \in \mathbb{N} \quad p \in P\ ; t \in T$$

$$\mathrm{Ptre}_{\mathrm{jt}} \in \mathbb{N} \quad j \in A\ ;\ t \in T$$

$$\mathrm{I}_{\mathrm{pt}} \in \mathbb{N} \quad p \in P\ ; t \in T$$

$$\mathrm{Itre}_{\mathrm{jt}} \in \mathbb{N} \quad j \in A\ ; t \in T$$

$$\mathrm{nbTD}_{\mathrm{pt}} \in \mathbb{N} \quad p \in P\ ; t \in T$$

$$\mathrm{a}_{\mathrm{jt}} \in \mathbb{N} \quad j \in A\ ; t \in T$$

$$\mathrm{b}_{\mathrm{pt}} \in \mathbb{N} \quad p \in P\ ; t \in T$$

$$besoin_{jt} \in \mathbb{N} \quad j \in A \;; t \in T$$

The constraints (1) and (2) determine the inventory level of product p at the end of period t. Constraints (3) ensure the conversion of the need for article j (expressed in km) into the number of units. This need will be injected into constraints (4) and (5). The constraints (4) determine the initial inventory level at period 1 which is equal to the inventory level of article j added to the quantity of article j needed to produce the product p. The constraints (5) determine the inventory level of article j at the end of period t. These two constraints ensure the synchronization of the two levels of production through the MRP logic which consists of deciding about the quantity of article j produced considering product p production. Constraints (6) and (7) detail storage capacity boundary of product p and article j. Family of constraints (8) and (9) identifies production capacity. As a result, the production of product p and article j must not exceed the maximum production capacity. Constraints (10), (11), (12) and (13) are used to establish the constraints (14) and (15): Indeed, in these four constraints, we introduce two intermediate variables a_{jt} and b_{pt} which take into account the minimum between the production capacity and the required produced quantity to have a maximum stock. The introduction of these two variables into constraints (14) and (15) ensures maximum use of production capacity. In addition to the maximum use of production capacity, these constraints ensure that production activity cannot take place unless it is bounded by a minimum threshold. Based on constraints (14) and (15), constraints (16) and (17) guarantee that once the maximum inventory level is reached, production activity is suspended until a minimum inventory level is reached. Constraints (18) determine the number of machines needed to produce product p during period t. Constraints (19) and (20) are applied to articles with a small section. Indeed, constraints (19) ensure that the first two articles are manufactured during the same period t. Whereas constraint (20) requires that the third article be not manufactured during the same period t as the first two articles. Constraints (21) and (22) are applied to articles with a medium section. Indeed, constraints (21) ensure that the 4th article is manufactured separately from other close section articles at period t. While constraint (22) requires that the last two articles of the same category be manufactured at the same period t. Constraints (23) are applied to articles with a large section. Indeed, they ensure that the two articles in this category are not manufactured during the same period t.

5. Computational experiments

During the current approach, a weekly planning horizon was adopted to manage the production activities. At the operational level, the focus was on detailing the quantities produced and stored per workstation. To improve processing time and facilitate data updates, the initial model was divided into three sub-models based on the category of each article (low section(M01), middle section(M02), and large section(M03)). Each article category is processed on a dedicated machine, eliminating the need for allocating machines to workstations in our specific case. By dividing the model into sub-models, the first aim is to streamline the optimization process and enhance efficiency in managing the production activities for different article categories.

5.1. Illustrative case

In this section, the model is illustrated through a detailed case study based on a specific activity of medium section articles production. The demand from the internal customer (extrusion area) at the operational level is known and remains constant on a weekly basis. Based on the bill of materials (BOM) for each product, the production plans for the Toroning and Wire drawing areas are established. The data for the model are presented in Table 1 below, providing the necessary inputs for the optimization process.

To ensure the system meets demands and maintains flexibility while optimizing resource utilization, certain thresholds and limits have been set for storage capacity. For strands products, the maximum storage capacity has been defined to provide a three-day coverage based on demand. On the other hand, the maximum storage threshold for drawn wire products is dependent on the available number of rails.

In addition to maximum storage capacities, minimum inventory levels have been established to meet the workstation's requirements. These levels ensure that there is sufficient inventory to support smooth operations at each workstation.

The production and storage capacity for products and articles can be found in Table 2, which provides a comprehensive overview of these parameters.

The operational model contains 1380 constraints and 2266 variables. To solve the model, we utilized the IBM ILOG CPLEX V12.3 package, which provided an optimal solution within a time of 8.40 s.

As part of our planning approach, the model was run four times, covering a one-month planning horizon. During this period, the average amount stored in the wire drawing area is equal to 49 units for a quantity of 5037.5 km in the toroning area. The results of the model are presented in an Excel sheet integrated within the CPLEX solver, as depicted in Table 3 and Table 4.

Additionally, Table 3 below displays the one-week production plan specifically for the wire drawing area, providing a visual

Table 1
Problem input Data.

Product	Demand/workstation (km)	Article used	Quantity (Coils)
P1	660	A1	1
P2	134	A2	5
		A3	1
P3	73	A3	3

Table 2
Production and storage capacity.

		Production capacity	Storage capacity
Products (km)	P1	700	6000
	P2	200	1300
	P3	100	700
Articles (coils)	A1	15	60
	A2	9	60
	A3	6	20

representation of the planned production activities.

This table shows that the production of Article 8*0.245 is completed by the end of the 1st day, while the production of Article 7*0.256 does not begin until the 3rd day on the second workstation. The presence of 4 empty workstations is because the inventory level of Article 7*0.256 does not reach its minimum requirement of 6 units until the end of the 3rd day on the first workstation. This example demonstrates the validity of our approach, which ensures that production can only occur when the minimum inventory level is reached. The same principle is illustrated in the production plan for the toroning area, as shown in Table 4.

5.2. Performance evaluations

In the three models (M01, M02, and M03), the average quantity stored in the wire drawing area is 187 units, while in the toroning area it is 9183.5 km. These results indicate an improvement in the storage activity.

Specifically, in the wire drawing area, there has been a gain of 247 coils stored. Since the storage rail capacity is 10 coils, this gain is equivalent to 25 rails of additional storage space.

In contrast, the stored quantity in the toroning area has decreased by 57899 km. This reduction represents a significant gain of 86.3 %.

Overall, these improvements in storage efficiency contribute to optimizing resource utilization and minimizing waste in the production process. Table 5 below provides a summary of the gains achieved.

The focus on minimizing work-in-process (WIP) has led to significant improvements in the lead time of the production system. Initially, the lead time was quite high at 43.83 days. However, through the implementation of the proposed solution, the lead time has been significantly reduced to 16.91 days. This represents a substantial saving of 27.71 days, resulting in a 62.10 % reduction in lead time.

The decrease in lead time is a direct result of optimizing the production process and reducing the amount of inventory held at different stages. By minimizing WIP, we have eliminated unnecessary waiting times and bottlenecks in the production flow. This has allowed for faster and more efficient processing of products, resulting in shorter lead times.

The reduction in lead time is a significant achievement as it has several benefits. Firstly, it improves the overall responsiveness of the production system, enabling us to fulfill customer orders more quickly. This can lead to increased customer satisfaction and loyalty.

Table 3
One-week production plan for M02 articles.

		Wire Drawing								
		7*0.256			8*0.245			10*0.245		
Day	Workstation	Production	Stock	requirements	Production	Stock	requirements	Production	Stock	requirements
1	P1	0	43	6	9	32	7	6	16	4
	P2	0	37	6	9	31	0	6	19	3
	P3	0	31	6	9	40	0	4	20	3
2	P1	0	25	6	0	40	0	0	17	3
	P2	0	19	6	0	40	0	0	14	3
	P3	0	13	6	0	40	0	0	14	0
3	P1	0	7	6	0	40	0	0	14	0
	P2	15	16	6	0	40	0	0	14	0
	P3	15	25	6	0	40	0	0	14	0
4	P1	15	34	6	0	33	7	0	12	2
	P2	15	43	6	0	26	7	0	10	2
	P3	15	52	6	0	19	7	0	8	2
5	P1	14	60	6	0	12	7	0	6	2
	P2	0	54	6	0	5	7	0	2	4
	P3	0	48	6	9	7	7	6	4	4
6	P1	0	42	6	9	9	7	6	6	4
	P2	0	36	6	9	11	7	6	8	4
	P3	0	30	6	9	13	7	6	10	4
7	P1	0	24	6	9	15	7	6	12	4
	P2	0	18	6	9	17	7	6	14	4
	P3	0	12	6	9	19	7	6	16	4

Table 4
One-week production plan for M02 products.

Stranding (toroning area)								
YA0035			YB0250			YB0150		
Production	NbT	stock	Production	NbT	stock	Production	NbT	stock
700	12	4340	184	2	1300	100	2	577
700	12	4380	0	0	1166	100	2	604
700	12	4420	0	0	1032	100	2	631
700	12	4460	0	0	898	100	2	658
700	12	4500	0	0	764	100	2	685
700	12	4540	0	0	630	0	0	612
700	12	4580	0	0	496	0	0	539
700	12	4620	0	0	362	0	0	466
700	12	4660	0	0	228	0	0	393
700	12	4700	200	2	294	0	0	320
700	12	4740	200	2	360	0	0	247
700	12	4780	200	2	426	0	0	174
700	12	4820	200	2	492	0	0	101
700	12	4860	200	2	558	100	2	128
700	12	4900	200	2	624	100	2	155
700	12	4940	200	2	690	100	2	182
700	12	4980	200	2	756	100	2	209
700	12	5020	200	2	822	100	2	236
700	12	5060	200	2	888	100	2	263
700	12	5100	200	2	954	100	2	290
700	12	5140	200	2	1020	100	2	317

Table 5
Storage activity savings.

	Initial state	Obtained stored quantities					
		End w1	End w2	End w3	End w4	Average Stored quantity	Gain achieved
Wire drawing area (coils)	434	186	142	228	191	187	247
Toroning area (km)	67082,5	11164	10586	6338	8646	9183.5	57899

Furthermore, the decreased lead time has a positive impact on operational efficiency and cost-effectiveness. With shorter lead times, we can better manage inventory levels, reduce holding costs, and optimize resource utilization. This can result in cost savings and improved profitability for the company.

Overall, the substantial reduction in lead time demonstrates the effectiveness of the current solution in streamlining the production process, minimizing WIP, and improving overall operational performance. The achieved lead time savings highlight the value and importance of our efforts in enhancing the efficiency and competitiveness of the production system.

The production approach, which emphasizes synchronization between production and storage activities, has yielded significant improvements in several key performance indicators. By implementing a strategy that considers production until reaching a maximum stock level and then suspending it until a minimum stock level is reached, we have effectively minimized the number of changeovers required per week. This reduction in changeovers has a direct impact on the productivity of the wire drawing machine.

As a result of the decreased number of changeovers, we have surpassed our target for the "Running time" performance indicator. The productivity rate has reached an impressive 95 %, exceeding the fixed target of 85.5 % and surpassing the initial value of 76 %. This indicates a substantial gain in terms of time, with an estimated improvement of 19 %. The increased productive time allows for more efficient utilization of the wire drawing machine, leading to enhanced productivity and output.

Furthermore, the model goes beyond determining the quantities to be produced and stored. It also considers the actual produced quantity rather than the requested quantity to determine the number of machines required in the toroning area to meet customer demands. This approach ensures that we have the exact number of stranding machines necessary and avoids any excess capacity. In fact, we have been able to reduce the number of stranding machines by 4, optimizing resource allocation and avoiding unnecessary costs.

6. Sensitivity analysis

6.1. Sensitivity analysis of demand

In the context of sensitivity analysis, running time serves as a crucial indicator that reflects the productive time of a machine. Its value is primarily influenced by the number of changeovers. Specifically, when there is an increase in demand, the production rotation of the same category of articles on a single machine within the wire drawing area can impact this indicator. Consequently, it becomes essential to evaluate the effect of such an increase on the running time indicator and assess the capability of the current approach to meet the corresponding demands.

During the current experiment, the impact of increased demand for products comprising medium section articles (M02) in the production lines, was investigated. These articles are widely used in the manufacturing processes. We specifically increased the demand for these products by 30 % over one week. The obtained results are summarized in Fig. 4.

From the results, it is evident that when a 30 % increase in demand is introduced, the number of changeovers in the production process significantly rises. In fact, the number of changeovers triples compared to the previous state. This increase occurs despite all workstations being fully utilized throughout the week. The primary reason behind this phenomenon is the heightened load imposed on the production system as a result of the increased demand.

The observed increase in the number of changeovers highlights the challenges associated with meeting the escalated demand for the medium section articles (M02).

To effectively manage this situation, it is necessary to assess and optimize the production system's capacity, workflow, and scheduling. By improving these aspects, it may be possible to reduce the number of changeovers and enhance the system's ability to meet increased demand more efficiently. This could involve strategies such as optimizing production sequencing, balancing workloads across workstations, or implementing lean manufacturing principles to minimize downtime and streamline operations.

Furthermore, the increase in demand resulting in a reduction in the number of unfilled workstations in the production schedule, indicates that the system has efficiently adjusted the production plan to address the important requirements of the toroning line by prioritizing the production of articles with faster changeover times.

While the proposed solution is able to meet the 30 % increase in demand, it is crucial to consider the potential impact of the increased number of changeovers on the running time indicator. The running time indicator is expected to be significantly affected by the higher number of changeovers, as they consume valuable productive time. This implies that maintaining the desired level of productivity may become challenging due to the time required for switching between different setups.

In light of these findings, exploring the possibility of acquiring another wire drawing machine becomes a viable alternative. By doing so, we can address the trade-off between maximizing production and maintaining the running time indicator within the intended objective. Introducing an additional machine would provide the necessary capacity to handle the increased demand while minimizing the impact on the running time indicator. However, a thorough study is required to evaluate the feasibility, cost-effectiveness, and long-term benefits of such an investment.

Ultimately, by carefully considering the obtained results and analyzing the implications of increased changeovers on the running time indicator, we can make informed decisions to optimize production processes and strike a balance between meeting demand and maintaining operational efficiency.

6.2. Managerial insights

The proposed multi-level integrated production-inventory planning approach applied to the industrial production of automotive wiring companies, achieving improvements in terms of running time, productive rate, and machine utilization, demonstrates its effectiveness, offering potential savings, enhanced efficiency, and competitive advantages through optimized operations planning. These results can be adopted by other industries with similar characteristics (multi-production, multi-level, multi-period), such as manufacturers of raw materials like textile yarns or fibers. The model's flexibility allows for seamless integration into different operational setups, accommodating variations in production scales, resource constraints, and specific industry requirements. This adaptability ensures that the model is not confined to a single context, but can be seamlessly incorporated into different environments, enhancing its usefulness across a range of production environments.

By synchronizing production and storage activities, we have not only minimized changeovers but also maximized productivity and

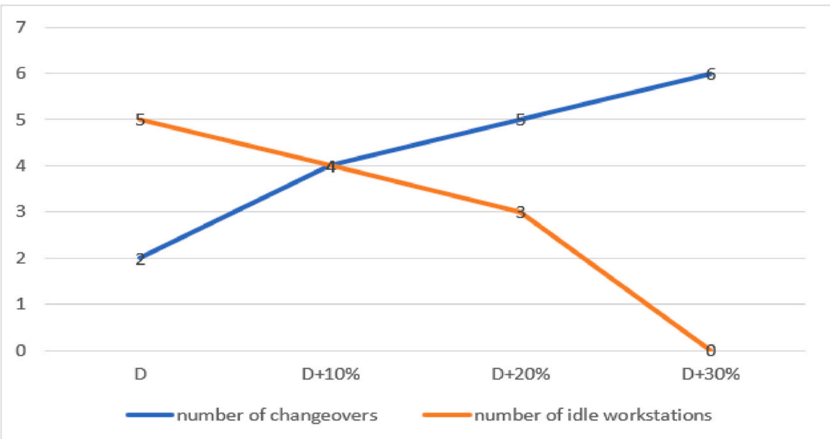

Fig. 4. The effect of increased demand on production planning.

resource efficiency. These achievements contribute to overall operational excellence and enhance the firm's ability to meet customer demands effectively.

Overall, the results highlight the importance of considering the impact of demand fluctuations on the production planning process, particularly in relation to the number of changeovers required. Addressing these challenges can help maintain operational efficiency and ensure the production system's ability to meet increasing demands effectively.

In the current situation, manufacturers cannot just focus on producing a lot of materials for automotive companies. They need to supply the right products at the right time with reasonable operational performance. To gain a competitive advantage, they should adopt a flexible and responsive approach to planning their production and inventory. By using more sophisticated methods to adjust production capacity, reduce changeovers, and accurately forecast replenishment orders, they can improve the performance of their supply chain.

This integrated production and inventory planning approach becomes even more important when demand increases. In fact, properly estimating stock quantities allows them to respond to the needs of automotive producers in real-time and make necessary adjustments in production accordingly.

Furthermore, this approach remains effective during disruptions like the COVID-19 pandemic. As seen during the pandemic, some automotive manufacturers had to change their priorities to meet the rising demand for electric vehicles and sustainable technologies. With integrated planning, manufacturers can quickly adjust their production and inventory activities to meet changing demands by focusing on high-demand products like electrical components used in electric vehicles.

7. Conclusions and further research

During this study, an operational planning approach that integrates production and storage activities, specifically focusing on the metal zone in automotive wiring industry was developed. This approach, which incorporates capacity and bill of materials (BOM) constraints, emphasizes the synchronization between two production phases. The results have demonstrated the significance of this integrated approach. In fact, in the toroning area, we achieved a substantial reduction in work-in-progress (WIP) of 86.3 %. This reduction in WIP contributes to better overall inventory management and operational efficiency. Additionally, in the wire drawing area, the integration of production and storage activities resulted in a space-saving of 25 rails. This optimization of space utilization is crucial for maximizing production capacity and resource allocation.

Furthermore, the lead time was significantly reduced by 27.71 days, enhancing the responsiveness and agility of the production system. The productive time of the wire drawing machine also saw a remarkable increase of 19 %, indicating improved machine utilization and productivity. Additionally, the number of stranding machines was reduced by 4, further streamlining the production process.

On one hand, these outcomes underscore the importance of synchronized production phases in the metal zone and highlight the benefits of integrated optimization of production and storage activities at the operational level. The significant gains achieved through this integration demonstrate its potential for enhancing operational performance and efficiency.

However, it is crucial to acknowledge that the management of the control loop (CL) operates on three decision-making levels: strategic, tactical, and operational. These hierarchical levels often involve separate planning processes, potentially hindering solutions' coherence. Thus, investigating the integration of these levels becomes essential for the automotive wiring industry.

By integrating strategic, tactical, and operational planning, a more holistic approach to optimizing production and storage emerges. This integrated approach addresses automotive wiring industry challenges, fostering efficiency, resource allocation, and overall performance enhancement. Future research should develop frameworks aligning these decision-making levels, enabling a coherent planning process.

On the other hand, sensitivity analysis revealed a substantial increase in changeovers (30 %) during a week with higher demand. This resulted from heightened production load, affecting unfilled workstations. While meeting demand, this spike impacts the running time indicator, challenging sustained productivity due to increased setup times.

Based on these findings, future directions and considerations should include.

- Exploration of alternative production strategies: Optimize sequencing, reduce changeover time, and enhance efficiency via batch optimization, advanced scheduling, and lean principles.
- Assessing extra resources: Evaluate acquiring a wire drawing machine to counter heightened changeovers, maintaining the running time indicator while considering costs, space, and long-term demand.
- Fostering continuous improvement: Cultivate a culture of enhancement by streamlining processes, minimizing waste, and boosting efficiency through key performance indicator analysis.
- Embracing new decision-making methods and Industry 4.0: Adopt methodologies like T-set theory, T-Pareto, and Neutrosophic, along with Industry 4.0 technologies (IoT, big data, automation) for improved decision-making and production optimization.
- Prioritizing sustainability and environmental concerns: Infuse eco-friendly practices into operational planning to minimize waste, optimize energy use, and consider lifecycle impacts.

Additionally, future research directions could explore the integration of advanced technologies such as artificial intelligence and machine learning algorithms to further enhance the accuracy and effectiveness of operations planning models in the automotive wiring sector.

By incorporating these cutting-edge technologies, the industry can continue to optimize its operational planning processes, improve productivity, and adapt to changing market demands, ultimately achieving sustainable growth and competitiveness.

CRediT authorship contribution statement

Imen Safra: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Kaouther Ghachem:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Faiza Benabdallah:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Hind Albalawi:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **Lioua Kolsi:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors extend their appreciation to the Deputyship for Research & Innovation, Ministry of Education in Saudi Arabia for funding this research work through the project number RI-44-0366.

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