

Article

Optimization Processes in Automotive Logistic Flow

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Abstract: This paper presents a logistic flow of assembling automotive rear axles. The product is presented in detail starting from the detailed research and analysis of relevant documentation about its functionality, including the manufacturing logistic flow diagram and the required equipment for the product manufacturing and assembly. This study is focused on optimizing the logistic flow for the manufacturing and assembly of automotive rear axles using WITNESS Horizon for system modeling and simulation in order to conduct system diagnostics, identify problems, and find solutions that will facilitate the optimization process. The study included a comprehensive assessment of the logistic flow, highlighting the performance of the equipment involved and identifying potential bottlenecks. Using the results obtained after the simulations, the Simplex linear mathematical method was applied to maximize production efficiency and profitability, considering the suppliers' capacity constraints and the components' delivery requirements. The results demonstrated a significantly optimized rear-axle production process, with increased profitability and improved productivity by eliminating identified bottlenecks. This research contributes to a deeper understanding of the complexities within the automotive industry and provides a solid foundation for continuously improving manufacturing and assembly processes.

Keywords: logistic flow; manufacturing and assembly; optimization; rear axle of motor vehicle



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1. Introduction

Automobiles play a significant role in modern society and have a profound impact on various aspects of life [1–3]. This paper studies the logistic flow of assembling the rear axle of a motor vehicle. The role of the rear axle of a motor vehicle is to take all the forces and moments that occur at the center of the rear wheels and transmit them to the frame or body of the motor vehicle using suspension springs and the wheel guide mechanism. Another role of the axle is to support the weight of the vehicle, passengers, and cargo, transmitting this load to the wheels and providing stability.

Nowadays, there is extensive research on optimizing solutions for improving production flows and improving manufactured products [4]. In these case studies, researchers have presented solutions to eliminate the defects from the logistic flow and decrease the cycle time, in order to increase the production capacity [5,6].

Such case studies were conducted by Muhammad Usman Yousaf et al., Shaowen Shao et al., Hu-Chen Liu et al., and Prasti A. Larasari et al. They can be analyzed and used for development in the automotive field [1,5–7]. The FMEA is used to identify potential failure modes (FMs), and it is crucial to determine the weights of risk factors and prioritize FMs. Another related study by Yanbing Ju et al. proposes a comprehensive framework that integrates the Dempster–Shafer theory, the best–worst method (BWM), stochastic multi-objective acceptability analysis (SMAA), and the measurement of alternatives and ranking according to compromise solution (MARCOS) to address this problem [3].

Another research team (Eheim M. et al.) considered automating manufacturing and assembly as a critical focus in the automotive industry, with the potential for significant time and cost savings [8]. The project presented in this paper aimed to automate the design and generation of wire harnesses for vehicles. The goal was to reduce design time and cost by at least 50%. This was to be achieved using graph-based design languages and the VEC (vehicle electrical container) as an open data standard.

Thelen et al. reviewed current digital twin trends across research disciplines and analyzed digital twin modeling and technologies, offering insights into the future trajectory of digital twin technology. Finally, their study introduces several emerging areas that are likely to be valuable for future digital twin studies. One of these areas is digital twinning for manufacturing architecture [9].

The authors Marcelus Fabri and Helena Ramalhinho studied the Internal Logistics Routing Management (ILRM) system, which consists of a set of logistics activities that a company performs to guarantee that workstations in an assembly line do not run out of parts. One of the activities studied is the design of supply routes. The ILRM is an operational and strategic system because it has an impact on the company's performance and uses both complex operational processes and systems. They evaluated the ILRM system in its initial form in which it uses fixed routes and proposed that variable routes be taken into account. Also, the authors evaluated different scenarios for the aspects related to the demand, namely the current demand, an automatic ordering system, and a demand forecast obtained from a manufacturing planning system to be transmitted to the suppliers. The authors managed to obtain positive results in reducing the transit time by using an Integer Linear Programming (ILP) and Iterated Local Search (ILS) program, which helped to calculate the variable routes and send them to the ILRM. From the point of view of optimization, the ILS program managed to calculate variable routes and reduce the distances traveled [10].

In another study [11] investigating delivery time reduction and transport cost reduction, the authors present a solution to solve the problem of transit time and high costs, and they argue that by reducing these costs, the company's income improves considerably.

In another study, the authors Sönke Wiczorrek, Christian Thies, Christian Weckenborg, Martin Grunewald, and Thomas S. Spengler investigated the subject of logistics and the supply sector. In the supply sector, supplier development is vital for material flows between partners. Their paper indicates that VWGL has implemented a collaborative approach for the development of suppliers in logistics, a field in which it is essential to identify suppliers that disrupt the flow and put manufacturing at risk and find production improvement solutions to apply to increase their logistic performance. This research consists of three stages: data preparation, measure evaluation, and measure allocation [12].

The authors Marcelus Fabri, Helena Ramalhinho, Miquel Oliver, and Juan Carlos Muñoz present a case study in which the main subject is an improvement in the internal logistic flow. The main key indicators are related to the performance of logistic flows (LPF) and the use of the corridors of an assembly line. The results obtained from the simulation show which corridors are overused; the disruptions in the logistic flows; and LPF, in terms of waiting for the parts to arrive at the workplace, the delivery time, and the length of the routes covered in distance and time [13].

In his paper, Xin Li presents how big data analytics is used to optimize logistics management by considering four key aspects: raw material costs, the efficiency of good delivery, one-stop solutions, and service evaluation [14]. In [15], some results are presented regarding the use of a CRM system to improve the quality of the process of producing components while improving the quality of the inputs, i.e., the quality of materials, the quality of the human factor, and the quality of the services provided in connection with the components.

The purpose of our paper is to study the production process flow and bottlenecks using an appropriate model within a digital twin of a manufacturing architecture. The proposed objectives are to see if a flow improvement is needed and to find solutions to

optimize the manufacturing process in order to increase productivity, reduce manufacturing costs, and increase sales. The studied flow has seven workstations with seven operators. Based on the observation of the way of work, the optimization of this logistic flow can be performed by reducing the cycle times required for the production process to manufacture the finished product and/or by performing technological optimization, reducing or adding work points, or by performing partial or total automation with the help of robots feeding robotic welding cells.

Based on the flow optimization, a significant improvement in the production time of the studied product is expected.

2. Materials and Methods

The product studied is presented in Figure 1.



Figure 1. Non-driving rear axle.

The rear axle of an automobile must meet certain conditions to provide optimal performance. It should have the smallest possible overall dimensions, particularly vertically, to maximize ground clearance. It should be as lightweight as possible, use the simplest technological solutions, and have the lowest possible costs. Additionally, it should have a long lifespan; be easy to maintain; offer high operational safety; and, last but not least, ensure the normal and quiet operation of its component mechanisms [16].

The classification of rear axles in an automobile is as follows:

Based on the vehicle's layout, rear axles are classified as follows:

1. Powered rear axles;
2. Non-powered rear axles.

Based on the type of steering mechanism, they are categorized as follows:

3. Rigid rear axles;
4. Semi-rigid rear axles;
5. Articulated rear axles.

2.1. Determining the Product Characteristics

As shown in Figure 2, the components of a rigid non-driven rear axle are as follows:

- 1—Bracket axle bushing;
- 2—Left rear trailing arm;
- 3—Support shock ABS;
- 4—Right rear trailing arm;
- 5—Cross-member;
- 6—Anti-roll bar;
- 7—Bracket anti-roll bar;

- 8—Cross-member reinforcer;
- 9—Left head axle;
- 10—Right head axle;
- 11—Left reinforcer axle head;
- 12—Right reinforcer axle head;
- 13—Reinforcer axle head;
- 14—Front reinforcer axle head;
- 15—Left reinforcer axle head;
- 16—Right reinforcer axle head;
- 17—Left spring support plate;
- 18—Right spring support plate;
- 19—Bracket brake pipe;
- 20—Left support cable;
- 21—Right support cable;
- 22—ABS bracket;
- 23—Left bracket rear-axle connecting member fairing;
- 24—Right bracket rear-axle connecting member fairing;
- 25—Bracket rear-axle connecting member fairing.

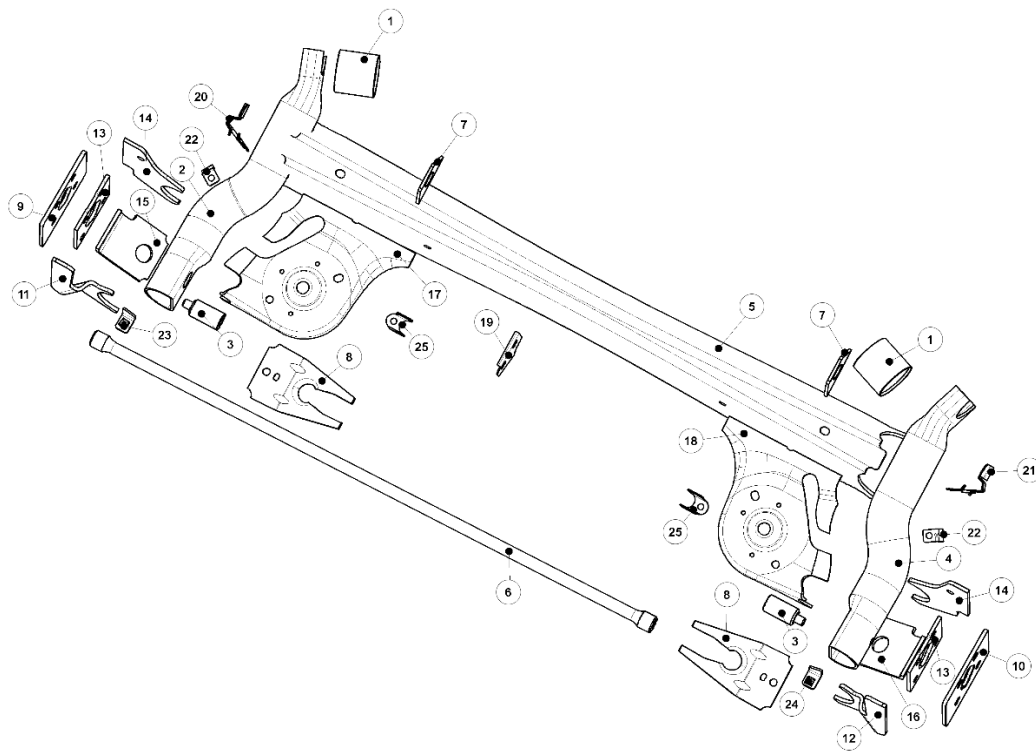


Figure 2. Components of a rigid non-driven rear axle.

Next, in Figures 3–20, details regarding all components of a rigid non-driven rear axle are presented.

- 1—The bracket axle bushing.

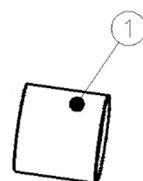


Figure 3. The bracket axle bushing.

Inside this support, the axle joints were mounted, after the deck had already passed the painting stage of the manufacturing process.

2, 4—Arm

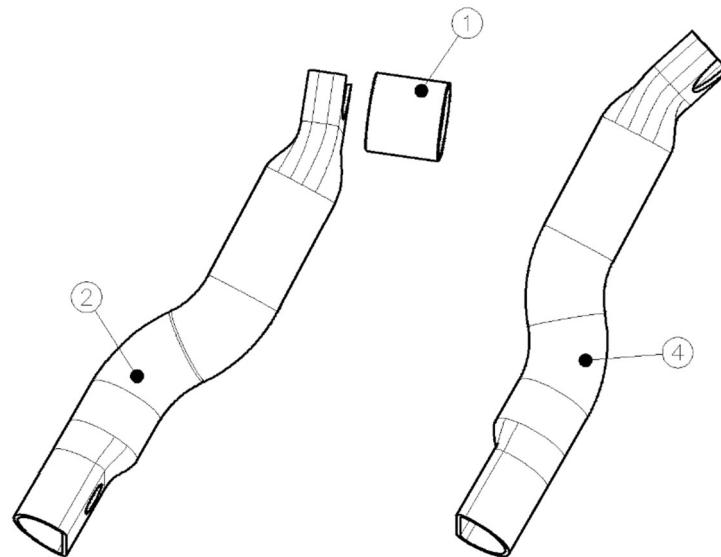


Figure 4. Arm.

In the upper end of the rear left/right arm 2/4, the support for the articulation of axle 1 was welded. The arm has the role of taking over the longitudinal forces and their moments.

3—Damper support

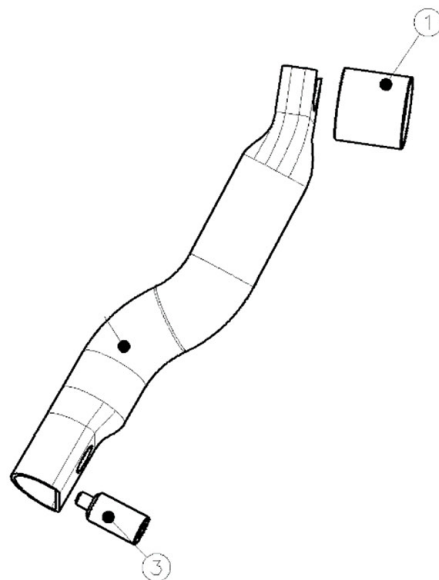


Figure 5. Damper support.

With the shock absorber support 3, the shock absorber was fixed to the rear axle of the vehicle. The role of the shock absorber is to take over the vibrations of the springs and reduce them in order to provide better comfort to the passengers. At the same time, it also has the role of making the connection between the deck and the body of the vehicle.

5—Connecting element

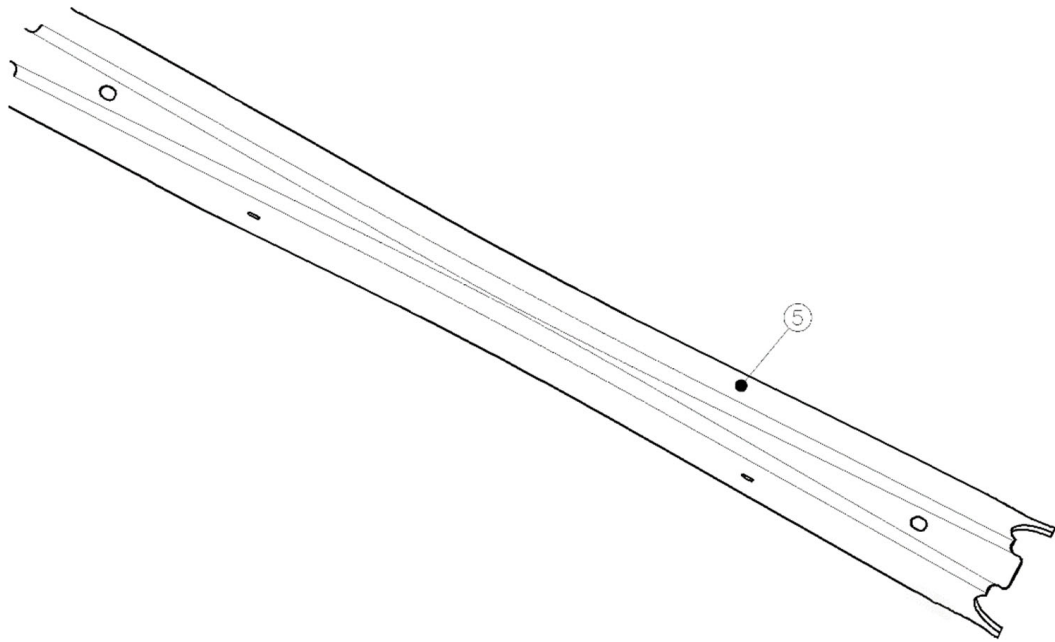


Figure 6. Connecting element (EDL).

In both ends of the connecting element 5, the subassembly consisting of the arm and support for the articulation of the axles was welded, which was also welded beforehand.

6—Anti-roll bar

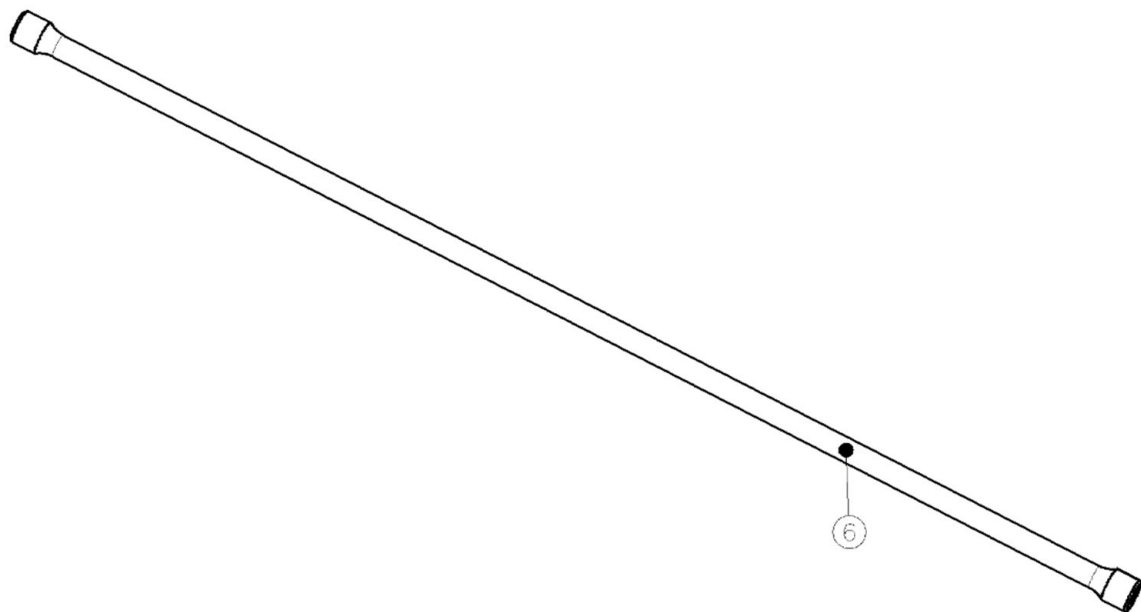


Figure 7. Anti-roll bar.

The anti-roll bar (6) was welded inside the connecting element (5). This is also called a stabilizer bar and has the role of ensuring the stability of the car in steep curves.

7—Anti-roll bar supports

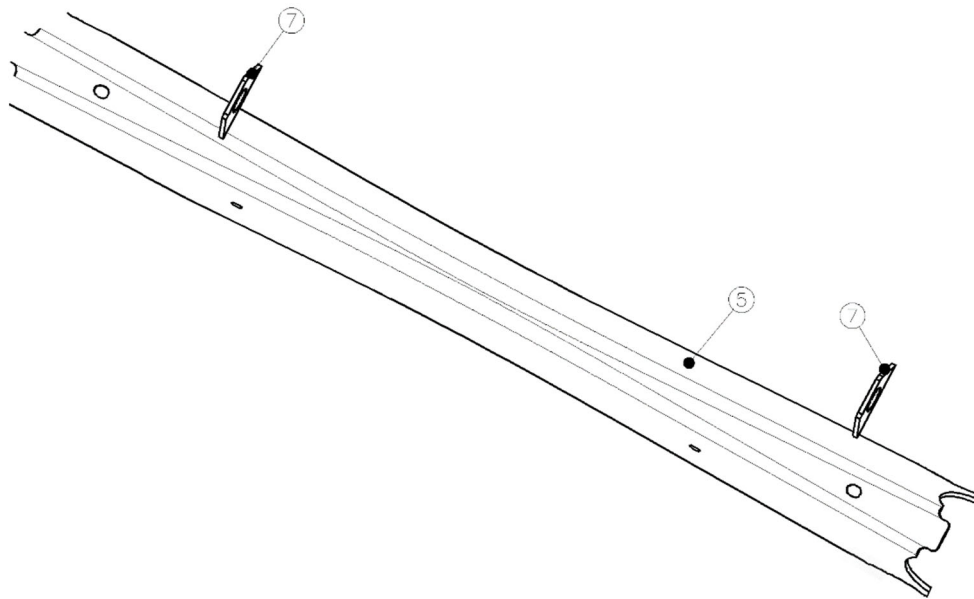


Figure 8. Anti-roll bar supports.

These supports were welded inside the connecting element (5), and on them, the anti-roll bar (6) was mounted, followed by welding. The role of these supports is that of supporting the anti-roll bar.

8—Gusset

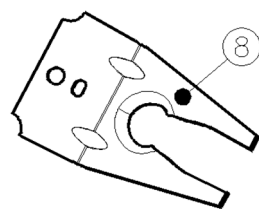


Figure 9. Gusset.

A gusset is a metal plate used to join several elements in a single node.

9, 10—Axle head left/right

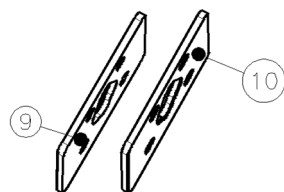


Figure 10. Axle head—left/right.

Metal plates 9 and 10 were used to strengthen the rear axle of the vehicle and ensure its rigidity.

11, 12—Rear-axle head reinforcement left/right



Figure 11. Left/right axle head reinforcement.

Reinforcements 11 and 12 are metal plates that have the role of strengthening the rigidity of the rear axle. They were mounted on the deck on both the left and right sides.

13—Axle head reinforcement



Figure 12. Axle head reinforcement.

Reinforcement 13 is a metal plate whose role is to stiffen the rear axle. This was mounted on both ends of the axle.

14—Rear head reinforcement

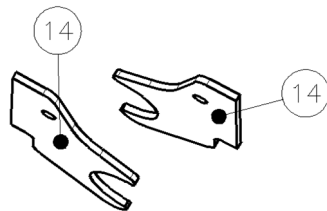


Figure 13. Rear head reinforcement.

Reinforcement 14 is a metal plate that helps strengthen the rear axle and ensures its rigidity.

15, 16—Reinforcement of the left/right lower axle head

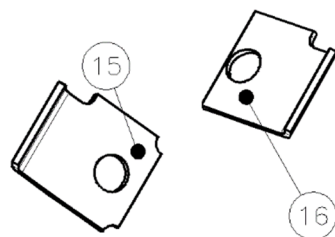


Figure 14. Lower axle head reinforcement.

Reinforcements 15 and 16 are metal plates that have the role of strengthening the rear axle of the vehicle and thus ensure the rigidity of the axle.

17, 18—Left/right spring support plater

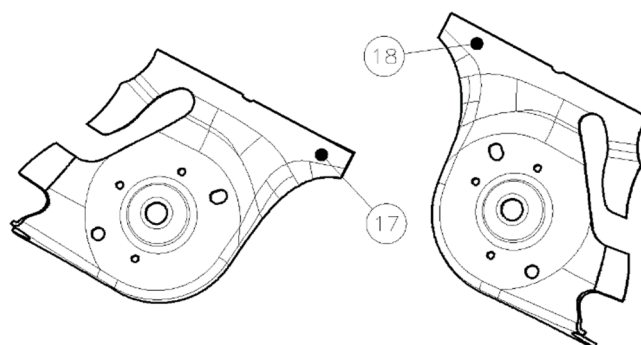


Figure 15. Left/right spring support plater.

The support platers for the spring have the role of supporting and fixing the springs on the rear axle of the vehicle. The role of the springs is to help the vehicle's suspension and absorb the shocks caused by the unevenness of the roads. They are taken up entirely by the springs if the bumps are not too large.

19—Brake pipe support

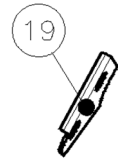


Figure 16. Brake pipe support.

The role of the support for the foot brake pipe (19) is one of fixing. With the help of this support, the pipe was fixed on the rear axle of the vehicle.

20, 21—Left/right brake cable support



Figure 17. Left/right brake cable support.

Supports 20 and 21 have the role of fixing the handbrake cable. The purpose of the handbrake is to lock the wheels of the vehicle when it is stationary.

22—ABS support

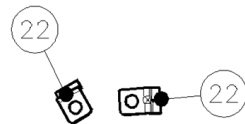


Figure 18. ABS Support.

With the help of these supports, the wiring for the ABS (anti-lock braking system) is fixed. The role of ABS is to prevent the vehicle's wheels from locking during braking and to allow the driver to have better steering control.

23, 24—Fairing support left/right

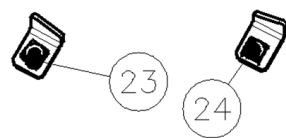


Figure 19. Fairing support left/right.

Attached to these mounts was a fairing that helps the car's aerodynamics and protects the spring mount (taler).

25—Fairing support connecting element

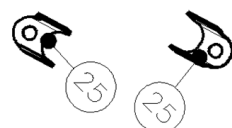


Figure 20. Fairing support connecting element.

Due to the fact that the connecting element has a “V” shape, in order to improve the aerodynamics of the vehicle, a fairing was attached to these supports, which also has the role of protecting the connecting element.

2.2. Description of the Logistic Flow Studied

The flow studied in this paper is a logistic flow for the manufacture and assembly of automobile rear axles. This flow is semi-automated and is composed of seven work points and seven operators. The role of the operators is to feed the robotic cells and prepare and check the decks.

2.2.1. Scheme of the Studied System

A diagram of the actual logistic flow of the manufacturing architecture was created in order to provide general information for system modeling in WITNESS Horizon, through which its functionality, production capacity, bottlenecks, and ways of optimization were studied.

WITNESS Horizon Version Release 25.0 is a software that can be used for modeling, simulation, and optimization flows that are present in any given domain. When conducting the modeling process using this software, one can reproduce the flow behavior using data from real life, thus creating the preliminary architecture. The real existing system was studied to gather information regarding the parameters used for cycle times, maintenance routine for each piece of equipment, speed of the transport systems, the human labor roles and work schedule, etc. Using the gathered data from the real system, a preliminary system architecture was modeled in WITNESS by defining equipment and labors; establishing the input and output rules for each element (equipment, labor, etc.); and defining cycle times, mean time between failures, mean time to repair, etc. Next, a preliminary simulation was run to gather information about the modeled system functionality. The validation of this phase was performed by comparing the results obtained through the WITNESS simulation with the data gathered from the real system. The model was calibrated by comparing the simulation results with actual production system results to ensure that the model accurately reflects real-world operations. Starting from this point, a diagnosis was performed to check the performance indicator levels and bottlenecks and to identify the necessary changes. Reports for all system elements were generated, and the results obtained for each workstation were interpreted to identify the necessary changes to be made. The proposed changes were studied and implemented into the WITNESS model. After the optimization process was completed, an optimized system architecture was obtained.

The diagram in Figure 21 illustrates the actual flow in the manufacturing process, for which the research was carried out. The following types of equipment were used within this stream:

1. Robotic welding cells;
2. Deck preparation station;
3. Rear-axle quality control post;

2.2.2. Description of the Logistic Flow

The manufacturing process starts with the operator (OP3) picking up the EDL parts, the anti-roll bar, the anti-roll bar support, and the gusset. They are placed in the robotic welding cell 1 and fixed, after which the button is pressed to start the robot welding process. After welding the four components, the first subassembly is obtained, which is picked up by the operator and placed on the transport system (C1) to the second robotic cell.

Within the robotic welding cell 3, the welding between the arm–bushing–damper shaft parts is performed. They are placed by the operator (OP1) on the cell feeding table and fixed, after which the welding process start button is pressed. Within cell 3, the second subassembly is made using the left/right shock arm–bush–shaft. After finishing the welding process, the parts are stored in a container in the station, and when the container is

filled with 500 parts, it is transferred with the help of a forklift (T1) to the robotic welding cell 2.

Robotic welding cell 2 welds Subassembly 1 (EDL + anti-roll bar + anti-roll bar support + gusset) with Subassembly 2 (arm + bushing + damper shaft) and two spring plates on the left and right sides. After welding these subassemblies and parts, the third subassembly is obtained (Subassembly 1 + Subassembly 2 left/right + Taler arch left/right). After welding Subassembly 3, it is picked up by the operator (OP2) from the station and put on the transport system (C2) to the preparation station.

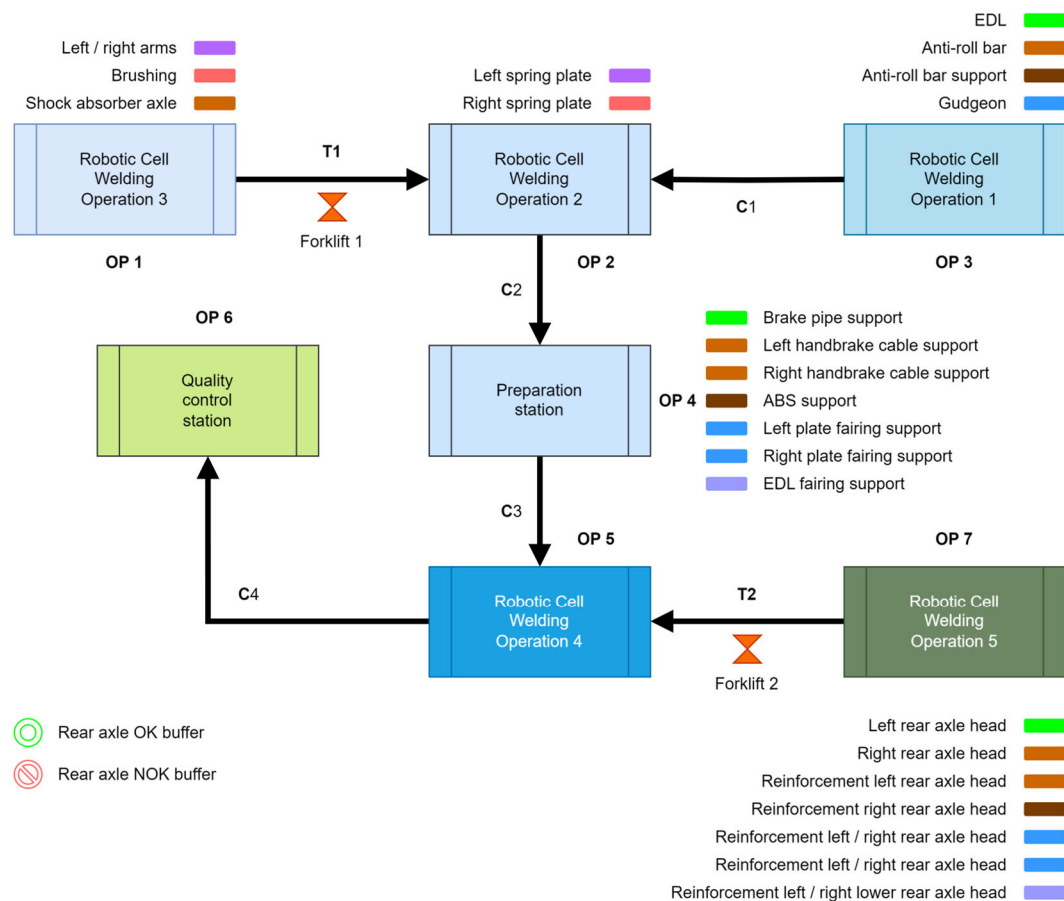


Figure 21. Rear-axle manufacturing logistic flow diagram.

In the preparation station, Subassembly 3 is taken by the operator (OP4), placed on the preparation table in the station, and fixed, after which the assembly of the following parts begins:

- Brake pipe support;
- Left handbrake cable support;
- Right handbrake cable support;
- ABS support;
- Left plate fairing support;
- Right-side plate fairing support;
- EDL fairing support.

After the preparation is finished, Subassembly 3 is transferred by the operator (OP4) on the transport system (C3) to the robotic welding cell 4.

Welding cell 4 performs the welding of Subassembly 3, which is formed in the previous stages, and Subassembly 4, which is made with the help of welding cell 5.

Within welding cell 5, the operator fixes the following parts on a feeding table to form Subassembly 4:

- Left axle head;
- Right axle head;
- Reinforcement of the left axle head;
- Reinforcement of the right deck head;
- Left/right axle head reinforcement;
- Left/right bridge head reinforcement;
- Left/right lower axle head reinforcement.

Two such subassemblies are welded at the same time, after which they are picked up by the operator (OP7) and placed in the container for storage. When the container is filled with 500 parts, it is transported to welding cell 4, using a forklift (T2).

The operator (OP5) takes two axle-head subassemblies from the container and fixes them on the feeding table and Subassembly 3, after which he presses the button to start the welding operation. After the welding process is finished, the operator takes the final formed assembly and places it on a gravity conveyor (C4) that carries out the transport to the quality control point.

The operator (OP6) takes the finished part and places it on the quality control table, where he inspects the part, whether it is conforming or non-conforming. In this position, the engraving of the traceability series corresponding to the batch is also carried out. For all welding cords, 100% visual control is expected. In addition, a visual check is conducted at each PO by the station operator. In case of non-conformity of the cords, a label is applied with the non-conforming cord number, and they are evacuated by the station operator on a cart with the identification of the defect on the applied label. All transport/transfer times performed by all seven operators were calculated and included as parameters in the flow in the modeling phase.

Next, the work points within the flow will be presented.

1. Robotic welding cells

In the composition of the flow, there are five robotic welding cells, which perform different stages in the manufacture of the studied product. These robotic cells are powered by human operators. Operators load the robotic cell table, fix the parts, move out of the robot's range, and then push the button to start the process. The cell doors close, and the robot begins to weld. After the welding process is finished, the doors open, and the operator takes the welded parts and positions them on the transport systems within the flow, directing them to the next equipment to perform the next step.

Technical specifications:

(a) Welding Robot:

- Model: Tropimatica WeldPro 2000;
- Type: articulated robotic arm;
- Number of axes: 6 axes;
- Load capacity: 10 kg;
- Range of action: 1600 mm;
- Positioning accuracy: ± 0.05 mm.

(b) Control System:

- Controller: Tropimatica RoboControl X200;
- Programming software: WeldSoft v3.5;
- User interface (HMI): 15-inch touch screen, intuitive graphical interface.

(c) Welding Equipment:

- Welding source type: TIG (tungsten inert gas), also known as tungsten inert gas arc welding;
- Shielding gas: gas mixture, such as Corgon 18 (82% argon and 18% CO₂);
- Electrode: non-fusible tungsten electrode, with copper head;
- Welding source power: 400 A;
- Welding parameters:

- Current: 50–400 A;
- Voltage: 16–40 V;
- Welding speed: 0.1–2.0 m/min.

- (d) Handling of Parts:
 - Grippers: pneumatic, adjustable for different sizes of parts;
 - Transport system: rotary table with precise positioning, load capacity 500 kg;
 - Fixing devices: hydraulic fixing devices, adjustable for various types of decks.
- (e) Production capacity:
 - Cycle time: 60–90 s per part (depending on the complexity of the weld);
 - Output: up to 40 pieces per hour.
- (f) Weld Quality:
 - Quality control: current and voltage monitoring sensors, automatic visual inspection of welds;
 - Correction systems: automatic correction of the welding path in real time.
- (g) Safety:
 - Protection devices: protective fences, safety interlocks, emergency stop;
 - Fault detection systems: collision sensors, automatic diagnostics, and emergency stop.
- (h) Installation and Maintenance:
 - Cell dimensions: 4 m × 4 m × 3 m;
 - Power requirements: 400 V, 50 Hz, 3 phases, 20 kW;
 - Operating conditions: temperature: 10–40 °C, humidity: 20–80% RH;
 - Maintenance: annual maintenance, quarterly lubrication, and spare parts available to order [17].

The technical specifications presented above are general technical specifications for a robotic welding cell similar to the one in the real flow.

In the logistic flow analyzed in this study, there are five such robotic cells, adapted for each stage of the manufacturing process. The differences between them consist of the table on which the parts are positioned; the programming of the robots for the welding movements; and the cycle times, which can vary.

2. Rear-axle preparation post

In the preparation station, there is a specially designed table with positioning and fixing systems for the rear axle so that there is no risk to the operator. In this position, the operator manually assembles the following components on the deck:

- Brake pipe support;
- Left handbrake cable support;
- Right handbrake cable support;
- ABS support;
- Left plate fairing support;
- Right plate fairing support;
- EDL fairing support.

These components are essential for the proper and safe operation of the vehicle's rear axle. The operator follows a strict assembly protocol to ensure accurate and efficient assembly, reducing the risk of errors and maximizing the quality of the final product.

3. Quality control post

For all welding seams, 100% visual inspection is expected.

In addition, a visual check is performed at each OP by the station operator. In case of non-conformity of the welding cords, a label with the number of the non-conforming welding cord is attached.

In this post, a macrographic quality control is carried out to determine the conformity or non-conformity of the product.

Macrographic quality control is an essential step in ensuring the integrity and compliance of the rear axle with the required quality standards. This verification involves the visual examination and analysis of the general appearance of components and assemblies to identify any surface defects or deviations from design specifications.

Within the macrographic control, the following activities are carried out:

- A. Visual inspection of surfaces:
 - Evaluation of the uniformity of the surface finish;
 - Identifying scratches, cracks, deformations, or other surface defects that could compromise the integrity of the structure.
- B. Checking dimensions and shapes:
 - Comparing component sizes and shapes to design specifications;
 - Using templates and measuring equipment to ensure compliance.
- C. Analysis of assemblies and fasteners:
 - Ensuring that all components are fitted correctly and are securely fastened;
 - Checking the exact positioning of the supports and other components fixed to the rear axle.
- D. Documentation of findings:
 - Recording all observations and findings in a detailed inspection report;
 - Photographing defect areas for documentation and to facilitate troubleshooting.
- E. Determination of Compliance:
 - Comparing inspection results with required standards and specifications;
 - Making decisions to accept or reject components based on the degree of conformity.
- F. Remedial Recommendations:
 - Providing suggestions and recommendations for correcting any deviations identified during the inspection;
 - Collaborating with the production team to implement the necessary corrective measures.

Macrographic quality control is a critical step in the quality assurance process, helping to detect problems early and prevent major defects that could affect the performance and safety of the rear axle in end-use. This control is essential for maintaining quality standards and meeting customer requirements.

The methods presented above are manual procedures for checking the quality of the studied flow, but to improve the quality control, vision sensors can be implemented on the flow, after each process performed on the rear deck, with which the quality control process can be automated, and thus the number of wastes produced can be reduced.

The artificial vision systems used for the inspection of products could mainly perform quality inspections to confirm the quality of a certain product or operation. However, these systems using dedicated automatic learning algorithms based on the data obtained in real time from the management system can lead to the reconfiguration of the system's material flow to enhance its performance. A challenge in this endeavor consists of the process of implementing and configuring the information flow associated with the material flow using different identification technologies that allow for greater flexibility and adaptability to new requirements related to quality and traceability.

By studying this logistic flow, we sought to obtain the following results and validations:

1. Improving process efficiency:
 - Reduction in cycle time for each assembly;
 - Optimizing the use of resources (materials, energy, time);
 - Increasing the production rate to meet delivery requirements.
2. Product quality improvement:

- Defect reduction by optimizing the welding and assembly processes;
 - Implementation of advanced quality control techniques to ensure uniformity and reliability of the final product;
 - Minimization of non-conformities and costs associated with subsequent repairs and replacements.
3. Reducing costs and risks:
- Identifying and eliminating non-value activities from the production process;
 - Reducing equipment operation and maintenance costs;
 - Reducing the risks associated with non-compliance with quality standards and regulations in force.

In general, the objectives of improvement and validation aim to improve process and product performance, reduce costs and risks, and comply with quality standards and legal norms, thus ensuring efficient, reliable, and sustainable production.

3. Results

3.1. Production Process Modeling of the Studied Manufacturing Architecture Using WITNESS Horizon

Figure 22 shows the preliminary manufacturing architecture modeled and simulated in WITNESS. The explanation of equipment in Figure 22 is presented in Table 1.

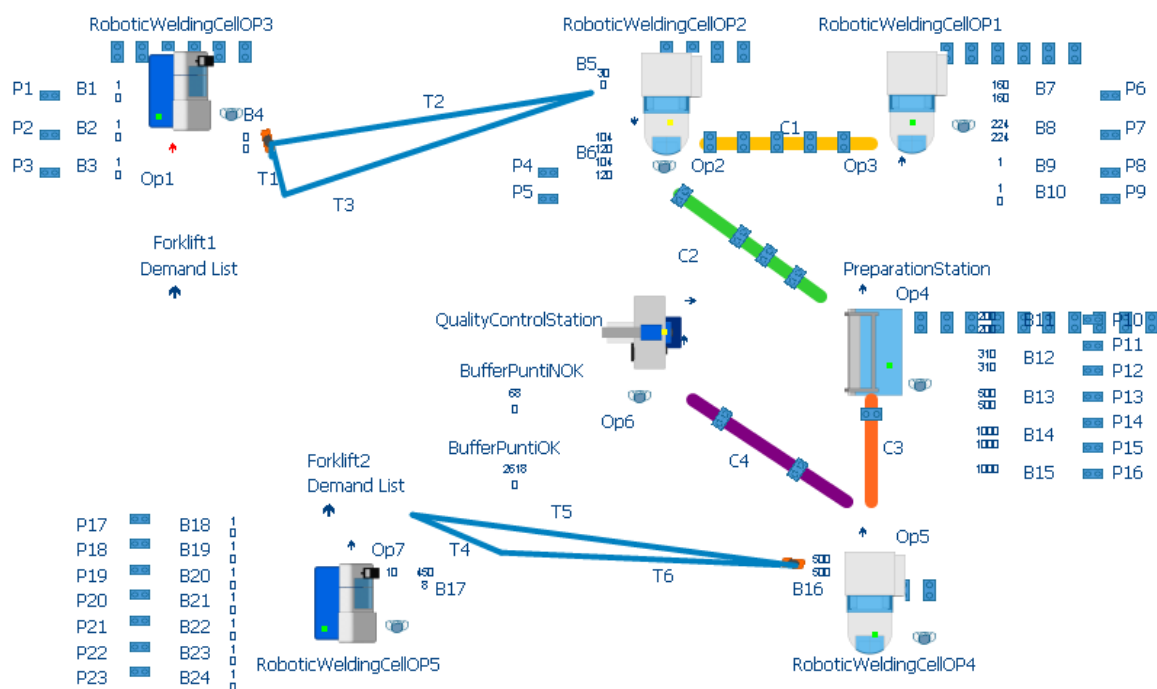


Figure 22. Preliminary manufacturing architecture.

Table 1. Element correspondence between equipment/elements names in WITNESS and equipment/elements from the preliminary manufacturing architecture.

Equipment/Element Name in WITNESS	Equipment/Element Name
RoboticWeldingCellOP1	Robotic Welding Cell Operation 1
RoboticWeldingCellOP2	Robotic Welding Cell Operation 2
RoboticWeldingCellOP3	Robotic Welding Cell Operation 3
RoboticWeldingCellOP4	Robotic Welding Cell Operation 4

Table 1. Cont.

Equipment/Element Name in WITNESS	Equipment/Element Name
RoboticWeldingCellOP5	Robotic Welding Cell Operation 5
PreparationStation	Preparation Station
QualityControlStation	Quality Control Station
P1	Arms Left–Right
P2	Bushing
P3	Shock Absorber Axle
P4	Left-Spring Support Plate
P5	Right-Spring Support Plate
P6	EDL (Cross-Member)
P7	Anti-Roll Bar
P8	Anti-Roll Bar Support
P9	Gudgeon
P10	Brake Pipe Support
P11	Left Handbrake Cable Support
P12	Right Handbrake Cable Support
P13	ABS Support
P14	Left Linear Support for the Fairing of the Spring Plate
P15	Right Linear Support for the Fairing of the Spring Plate
P16	Rear-Axle Connecting Member Fairing Support
P17	Left Rear-Axle Head
P18	Right Rear-Axle Head
P19	Reinforcement Left Rear-Axle Head
P20	Reinforcement Right Rear-Axle Head
P21	Reinforcement Left/Right Rear-Axle Head
P22	Reinforcement Left/Right Rear-Axle Head
P23	Reinforcement Left/Right Lower Right-Axle Head
B1	Buffer Arms Left–Right
B2	Buffer Bushing
B3	Buffer Shock Absorber Axle
B4	Buffer Subassembly Arm Bushing ABS1
B5	Buffer Subassembly Arm Bushing ABS2
B6	Buffer Spring Plate Support
B7	Buffer EDL (Cross-Member)
B8	Buffer Anti-Roll Bar
B9	Buffer Anti-Roll Bar Support
B10	Buffer Cross-Member Reinforcement
B11	Buffer Brake Pipe Support
B12	Buffer Left/Right Handbrake Cable Support
B13	Buffer ABS Support
B14	Buffer Left/Right Fairing Support

Table 1. Cont.

Equipment/Element Name in WITNESS	Equipment/Element Name
B15	Buffer EDL Fairing Support
B16	Buffer Subassembly Rear-Axle Head 2
B17	Buffer Subassembly Rear-Axle Head 1
B18	Buffer Left Head Axle
B19	Buffer Right Head Axle
B20	Buffer Left Rear-Axle Reinforcement
B21	Buffer Right Rear-Axle Reinforcement
B22	Buffer Left/Right Axle Head Reinforcement
B23	Buffer Left/Right Rear-Axle Head Reinforcement
B24	Buffer Left/Right Inferior Axle Head Reinforcement
B25	BufferRearNOK
B26	BufferRearOK
C1	Conveyor1
C2	Conveyor2
C3	Conveyor3
C4	Conveyor4
T1 + T2 + T3	Forklift1 Route
T4 + T5 + T6	Forklift2 Route
Op1	Operator1
Op2	Operator2
Op3	Operator3
Op4	Operator4
Op5	Operator5
Op6	Operator6
Op7	Operator7

Within the manufacturing architecture, work points were created for each operation required to manufacture the rear axle.

To evaluate the production capacity in a work week with three shifts per day of eight hours each, and a production gap of eight hours, a simulation was performed for a total duration of 6960 min for the manufacturing architecture. This architecture can produce 2618 rear axles per week and approximately 68 scraps, which can be recoverable or non-recoverable, depending on the degree of defect.

Work points within the manufacturing architecture are presented In Figures 23–29.

Robotic cell 1:

“Robot welding cell operation 1” performs the welding operation between the Link Element (EDL), the anti-roll bar, the supports for the anti-roll bar, and the gussets.

The elements that are welded within this work point are placed and picked up manually by a human operator, named in the manufacturing architecture “Operator 3”.

This first subassembly obtained after the welding operation in robotic cell 1 is transported with the help of conveyor C1 to work point two, i.e., “Robot cell welding operation 2”.

Robotic cell 3:

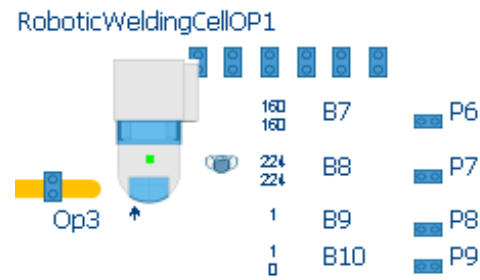


Figure 23. Robotic cell 1.

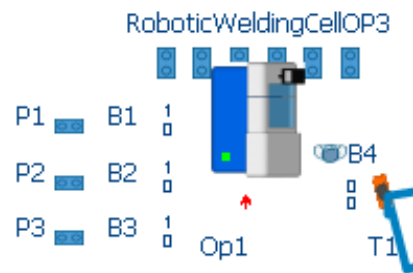


Figure 24. Robotic cell 3.

In this work point, “Robot welding cell operation 3”, the second subassembly is obtained, comprising an arm, bushing, and damper shaft. With the help of this cell, this subassembly is obtained for both the left and right sides of the bridge at the same time.

After obtaining each subassembly, “Operator 1” places it in the specific container for the left or right, and after filling them, they are picked up by a forklift and transported to robotic cell 2.

Robotic cell 2:

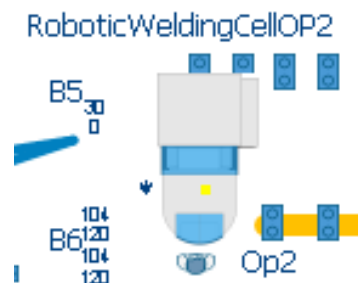


Figure 25. Robotic cell 2.

In the second robotic cell, the first subassembly is obtained at the first working point, and the second subassembly consisting of an arm, bushing, and damper is obtained with the help of robotic cell 3, and the spring plate is welded.

After welding them, “Operator 3” takes this obtained assembly and places it on the C2 conveyor that transports it to the “preparation station”, where it is taken over by “Operator 4”.

Rear-axle preparation post:

In the “preparation station”, “Operator 4” mounts the following parts on the sub-assembly obtained in the previous stages: one support for the brake pipe; two supports for the handbrake cable; and on the left and right sides of it, two ABS brackets, two fairing brackets protecting the spring plate, and two fairing brackets protecting the EDL.

After fitting the parts listed above, the operator places the assembly on conveyor C3, which transports the assembly to the “Robot welding cell operation 4”.

Robotic cell 5:

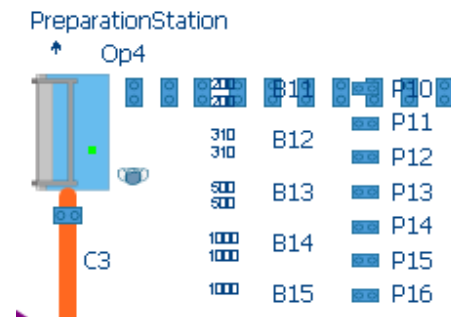


Figure 26. Rear-axle preparation post.

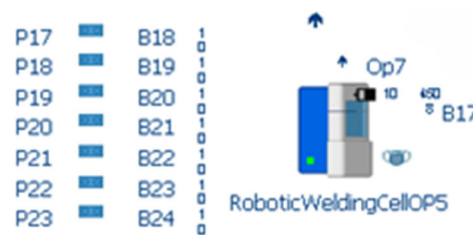


Figure 27. Robotic cell 5.

Within this cell, Subassembly 3 is obtained, which consists of the following parts: left and right axle head, left and right axle head reinforcement, left and right axle head reinforcement, left axle head reinforcement, and right and lower axle head brace for left and right.

This obtained subassembly fits in both ends of the rear axle.

Within the robotic cell, two subassemblies can be welded at the same time. The parts are placed manually by “Operator 7” and are also picked up after welding by the operator and placed in the container for storage. After the container is filled, it is transported to robotic cell 4 with the help of a forklift.

Robotic cell 4:



Figure 28. Robotic cell 4.

With the help of robotic cell 4, the final assembly consisting of the axle-head subassembly 3 and the assembly prepared in the previous stages is made.

The assembly previously prepared in the preparation station and transported by the conveyor C3 is taken by Operator 5 and placed inside robotic cell 4, after which two subassemblies made within robotic cell 5 are placed: one on the left side and one on the right side.

Within cell 4, the last welding operation on the deck is carried out. After its completion, Operator 5 takes the bridge and places it on conveyor C4, which transports it to the quality control point.

Post quality control:

In this position, a visual control is carried out by Operator 6 on the welds, and the engraving of the bridge series is carried out with the help of a milling cutter in order to have traceability on the production.



Figure 29. Post quality control.

After carrying out the quality control and engraving, the operator takes the deck and stores it on a scale suitable for the decks considered OK or NOK, where they are stored and picked up for the next stages of processing.

The mean time between failures as well as the mean time to repair all equipment were defined in the preliminary system according to their technical data sheets but also based on statistics of the real system.

Following the simulation of the manufacturing architecture, the results were obtained, which can be found in the reports below.

In Figure 30, one can see the operating percentage of each work point, but also the waiting percentage of the parts.

Report for working points:

Name	% Idle	% Busy	% Filling	% Emptying	% Blocked	% Cycle Wait Labor	% Setup	% Setup Wait Labor	% Broken Down	% Repair Wait Labor	No. Of Operations
CelulaRob...	44.822	55.178	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2695
CelulaRob...	33.621	66.330	0.000	0.000	0.049	0.000	0.000	0.000	0.000	0.000	3239
CelulaRob...	28.756	71.244	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3479
PostDePr...	42.024	57.976	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2690
CelulaRob...	44.956	55.044	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2688
PostContr...	61.408	38.592	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2686
CelulaRob...	28.756	71.244	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3479

Figure 30. The degree of operation of the work points.

In Figure 31, one can graphically observe the values from Figure 31. Green means the degree of operation of each work point, and yellow means their waiting time.

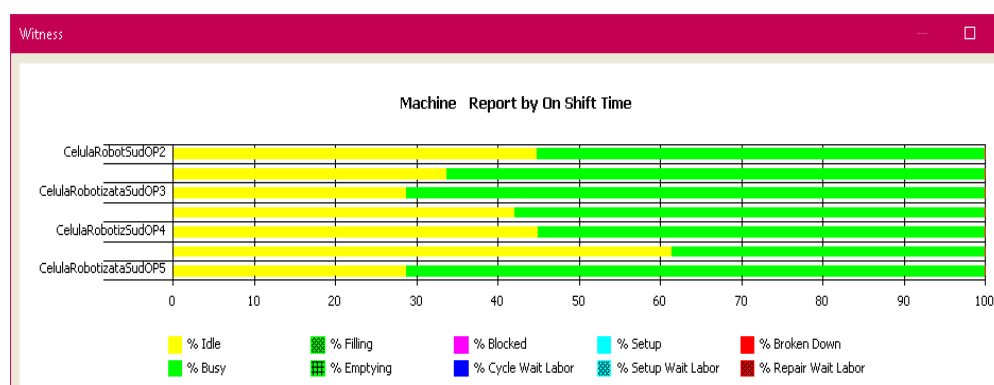


Figure 31. The graphic report of the work points.

Figure 32 shows the operating percentage of the conveyors used to transport parts between work points.

Conveyor report:

In the graphic report in Figure 33, the degree of the operation, waiting, queue or blockage of the conveyors in the manufacturing architecture can be observed in percentage, where green represents the operation, yellow indicates waiting for parts, blue indicates the queue of parts on the conveyor, and pink indicates the degree of blockage.

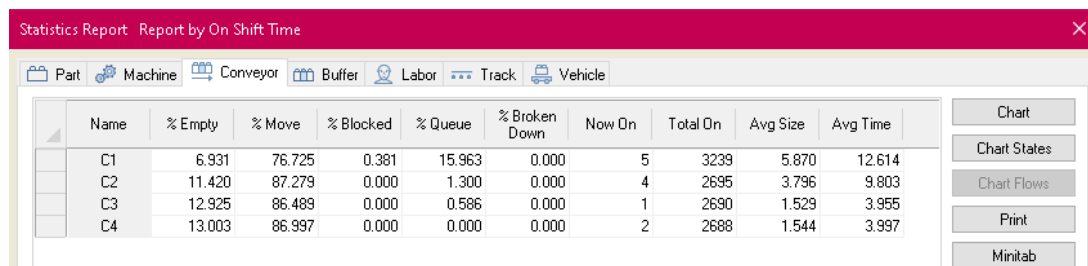


Figure 32. The degree of operation of the conveyors.

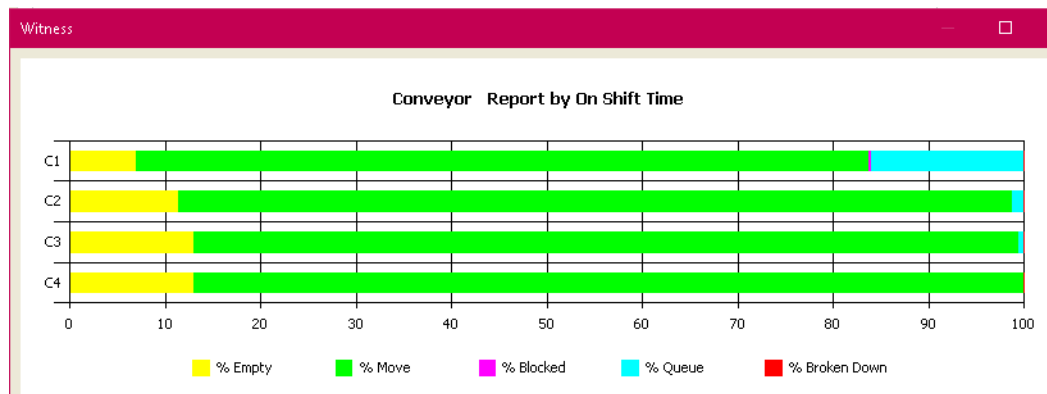


Figure 33. The graphic report of the degree of operation of the conveyors.

Figure 34 shows the graphic report of the percentage of work of the operators.

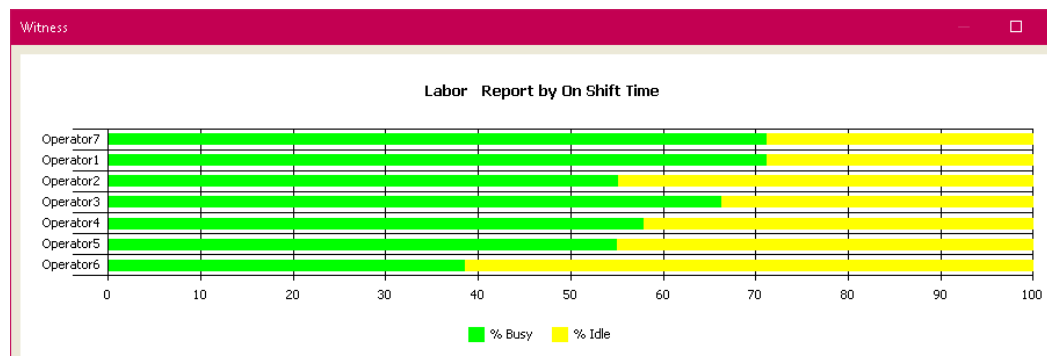


Figure 34. The graphic report of the degree of work of the operators.

In the report in Figure 35, one can see the operating percentage of the two machines used to transport parts between work points.

Report for forklifts:

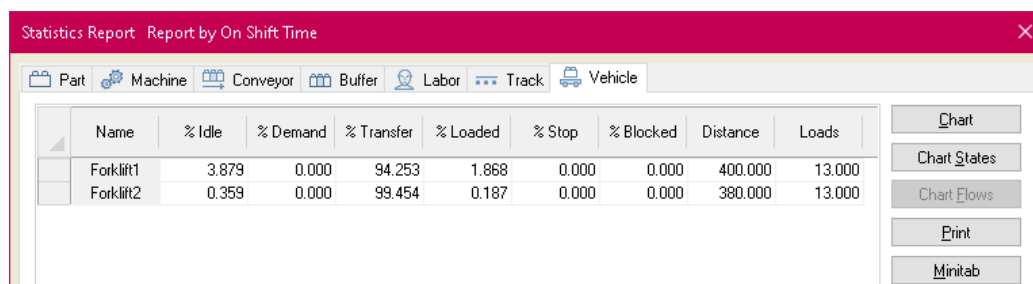


Figure 35. Operating percentage of forklifts.

Figure 36 shows the graphic ratio of the utilization of the two forklifts, where green means the percentage in which the forklift is loaded, blue means the transfer, and yellow means the waiting degree.

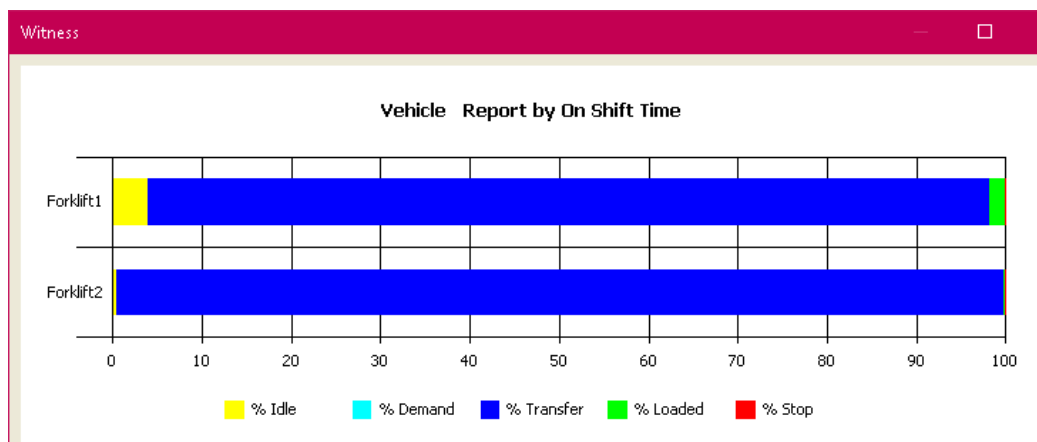


Figure 36. Graphic report of forklift usage.

After simulating the non-optimized manufacturing architecture, it was found that this architecture could produce 2618 rear axles per week. This reflects a robust production capability, but there is room for improvement to reduce scrap and optimize cycle times.

The analysis of the degree of operation of the work points (Figures 31 and 32) shows that there are significant variations in the use of different work points. Some workstations have high waiting times, indicating possible inefficiencies in the production flow.

Weekly production generates approximately 68 scraps, which may be salvageable or non-salvageable depending on the degree of defect. This suggests the need to implement more rigorous quality control measures and process optimization to reduce the scrap rate.

Each robotic cell has different specifications and cycle times. Variability in cell performance indicates the need to adjust and synchronize them to ensure a continuous and balanced flow of production.

The quality control station (Figure 30) plays a crucial role in ensuring product conformity. Improving quality control techniques and implementing standardized procedures can reduce the number of non-conforming parts and improve production traceability.

The conveyor and forklift utilization report (Figures 33–36) shows a variable degree of utilization with waiting periods and bottlenecks. Optimizing the use of this equipment can contribute to a better flow of production.

Possible solutions for optimization:

1. Reducing waiting times: implementation of production flow synchronization measures to minimize waiting times at work points and conveyors;
2. Improving quality control: adoption of advanced quality control techniques to reduce the scrap rate and ensure better product traceability;
3. Optimizing resource utilization: redistributing tasks and adjusting the work schedule of operators and equipment to maximize efficiency and productivity, and to prevent worker fatigue and errors, the operators work in 8 h shifts with 3 breaks (one half-hour lunch break and two 15 min breaks);
4. Robotic cell synchronization: adjusting cycle times and robot scheduling to ensure better harmonization between different stages of the manufacturing process;
5. Analysis and implementation of improvements: continuous use of simulations to test and evaluate the impact of various proposed improvements on the entire production system.

3.2. Optimization of the Production Process in WITNESS Horizon

Figure 37 shows the manufacturing architecture after optimization made in WITNESS. The explanation of equipment in Figure 37 is presented in Table 2.

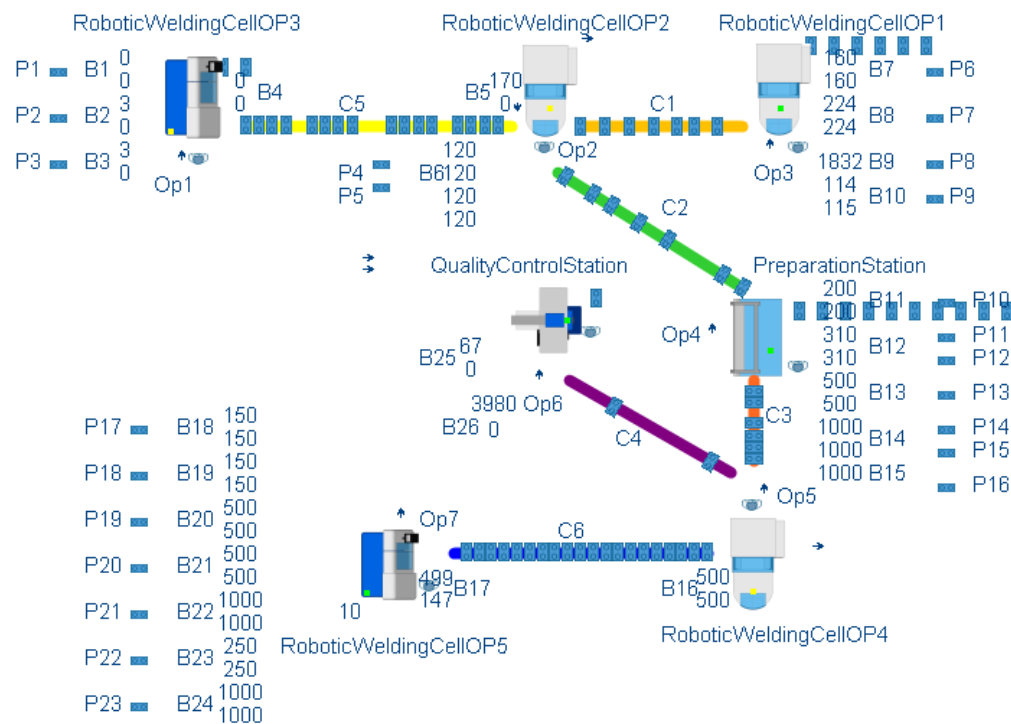


Figure 37. Manufacturing architecture after optimization.

Table 2. Element correspondence between equipment/elements names in WITNESS and equipment/elements from the optimized manufacturing architecture.

Equipment/Element Name in WITNESS	Equipment/Element Name
RoboticWeldingCellOP1	Robotic Welding Cell Operation 1
RoboticWeldingCellOP2	Robotic Welding Cell Operation 2
RoboticWeldingCellOP3	Robotic Welding Cell Operation 3
RoboticWeldingCellOP4	Robotic Welding Cell Operation 4
RoboticWeldingCellOP5	Robotic Welding Cell Operation 5
PreparationStation	Preparation Station
QualityControlStation	Quality Control Station
P1	Arms Left–Right
P2	Bushing
P3	Shock Absorber Axle
P4	Left Spring Support Plate
P5	Right Spring Support Plate
P6	EDL (Cross-Member)
P7	Anti-Roll Bar
P8	Anti-Roll Bar Support
P9	Gudgeon
P10	Brake Pipe Support

Table 2. Cont.

Equipment/Element Name in WITNESS	Equipment/Element Name
P11	Left Handbrake Cable Support
P12	Right Handbrake Cable Support
P13	ABS Support
P14	Left Linear Support for the Fairing of the Spring Plate
P15	Right Linear Support for the Fairing of the Spring Plate
P16	Rear-Axle Connecting Member Fairing Support
P17	Left Rear-Axle Head
P18	Right Rear-Axle Head
P19	Reinforcement Left Rear-Axle Head
P20	Reinforcement Right Rear-Axle Head
P21	Reinforcement Left/Right Rear-Axle Head
P22	Reinforcement Left/Right Rear-Axle Head
P23	Reinforcement Left/Right Lower Right-Axle Head
B1	Buffer Arms Left–Right
B2	Buffer Bushing
B3	Buffer Shock Absorber Axle
B4	Buffer Subassembly Arm Bushing ABS1
B5	Buffer Subassembly Arm Bushing ABS2
B6	Buffer Spring Plate Support
B7	Buffer EDL (Cross-Member)
B8	Buffer Anti-Roll Bar
B9	Buffer Anti-Roll Bar Support
B10	Buffer Cross-Member Reinforcement
B11	Buffer Brake Pipe Support
B12	Buffer Left/Right Handbrake Cable Support
B13	Buffer ABS Support
B14	Buffer Left/Right Fairing Support
B15	Buffer EDL Fairing Support
B16	Buffer Subassembly Rear-Axle Head 2
B17	Buffer Subassembly Rear-Axle Head 1
B18	Buffer Left Head Axle
B19	Buffer Right Head Axle
B20	Buffer Left Rear-Axle Reinforcement
B21	Buffer Right Rear-Axle Reinforcement
B22	Buffer Left/Right Axle Head Reinforcement
B23	Buffer Left/Right Rear-Axle Head Reinforcement
B24	Buffer Left/Right Inferior Axle Head Reinforcement
B25	BufferRearNOK

Table 2. Cont.

Equipment/Element Name in WITNESS	Equipment/Element Name
B26	BufferRearOK
C1	Conveyor1
C2	Conveyor2
C3	Conveyor3
C4	Conveyor4
C5	Conveyor5
C6	Conveyor6
Op1	Operator1
Op2	Operator2
Op3	Operator3
Op4	Operator4
Op5	Operator5
Op6	Operator6
Op7	Operator7

Following the optimization of the manufacturing architecture, production capacity increased from 2618 decks to 3980 parts per week. Both functional and technological optimization procedures were performed on the manufacturing architecture.

- a. The functional optimization consisted of the following changes:
 1. The entry time of parts into the manufacturing flow was reduced;
 2. The cycle time for work points was decreased, as can be seen in Table 3.
- b. The technological optimization consisted of the following changes:
 3. Forklift 1 was removed from the flow and replaced with conveyor C5;
 4. Forklift 2 was removed from the flow and replaced with conveyor C6.

Following the preliminary simulation, blockages related to the handling of materials generated by forklifts were identified. These blockages were reduced by replacing forklifts with conveyors, which facilitated the reduction in transport time between different workstations. Following the optimization, all the changes made to the flow, including the replacement of forklifts, led to an increase in productivity.

The mean time between failures as well as the mean time to repair were defined for the new proposed equipment from the proposed optimized system architecture. The proposed solutions for the replacement of the different equipment within the flow were made based on the performance described in their technical data sheet. The initial simulation results led to an additional analysis of the technical equipment used in order to be able to identify solutions for configuring the flow, taking into account the performance of some equipment that can perform similar tasks in the logistics processes. The performance of the technical systems used to handle the products plays an important role in the performance of the material flow, and therefore using a dedicated software application, one can obtain predictable data for the better functioning of the material flow in relation to the performance of the equipment.

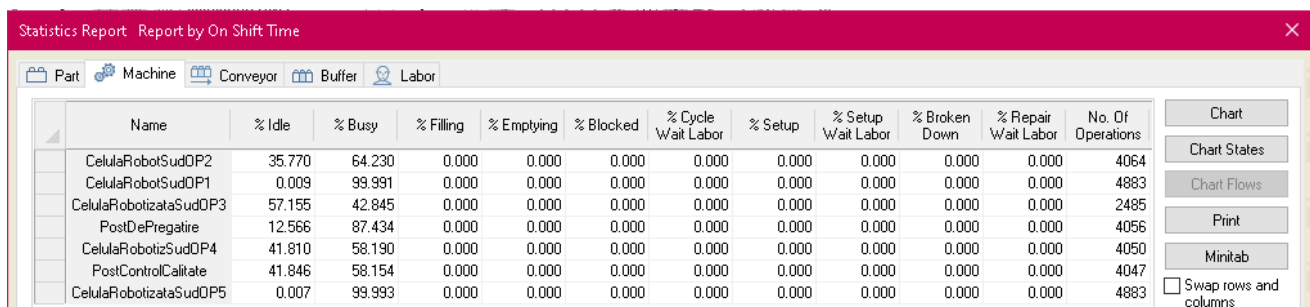
In the reports below, the results obtained from the previously mentioned optimizations are presented.

Figure 38 shows the operating and waiting percentages of the work points in the manufacturing flow.

Report working points:

Table 3. Parameter values used in the manufacturing architecture before optimization and after optimization.

Component Elements—Manufacturing Architecture	Parameter Values Used Before Optimization	Parameter Values Used After Optimization
Cell Robot Sud OP1	1.425	1.425
Cell Robot Sud OP2	1.425	1.1
Cell Robot Sud OP3	1.425	1.2
Cell Robot Sud OP4	1.425	1
Cell Robot Sud OP5	1.425	1.425
Post Preparation	1.5	1.5
Post Quality Control	1	1
C1	0.5	0.5
C2	0.5	0.5
C3	0.2	0.2
C4	0.2	0.2
C5	-	0.5
C6	-	0.5
Forklift1 (T1 + T2 + T3)	1	-
Forklift2 (T4 + T5 + T6)	10	-

**Figure 38.** The degree of operation of the work points after optimization.

For example, the welding robotic cell OP2 had a waiting percentage of 35.77% after optimization, compared to 44.822% before optimization, and an uptime of 64.23% compared to 55.178%. To be able to compare the results obtained before optimization and after optimization, the presented reports can be compared (Figures 31 and 39).

Figure 39 graphically shows the degree of operation and waiting of the work points shown in Figure 38, where green signifies the degree of operation, and yellow indicates the degree of waiting.

Figure 40 shows the degree of functionality of the conveyors within the manufacturing flow. Five of the six conveyors had a movement percentage of over 90%. The only conveyor on which there were blockages was the C6 conveyor.

Conveyor report:

Figure 41 shows the graphical report of conveyor operation, showing the values in Figure 40. To see the differences in operation before and after optimization, Figures 33 and 41 can be compared.

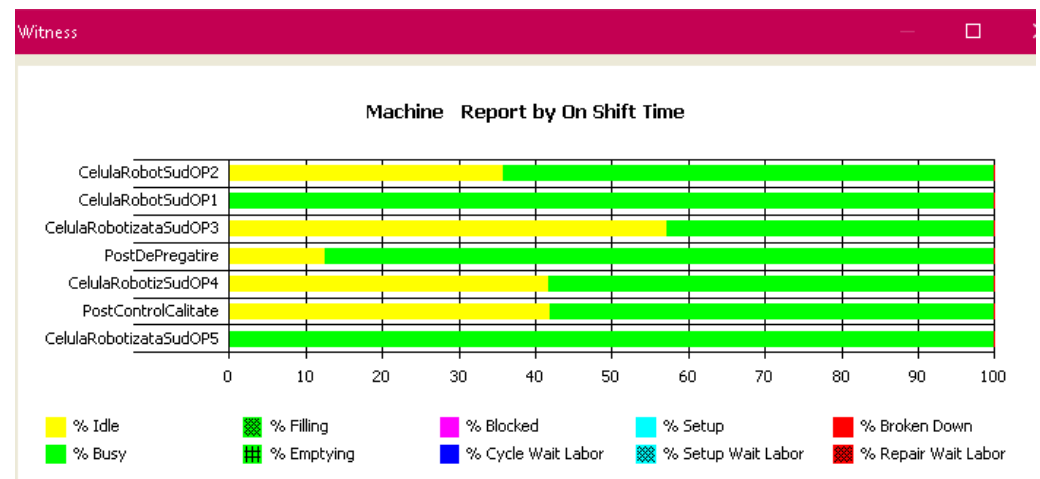


Figure 39. The graphic report of the degree of operation of the work points.

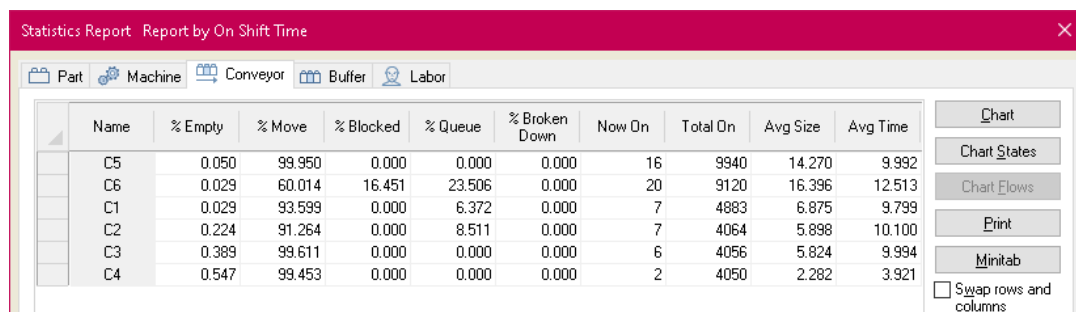


Figure 40. Conveyor efficiency report after optimization.

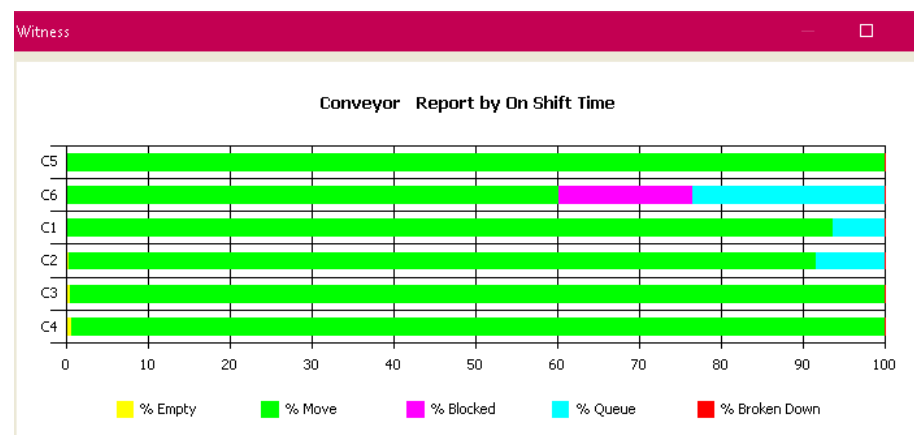


Figure 41. The graphic report of the degree of operation of the conveyors after optimization.

After optimizing the manufacturing architecture, we can draw several important conclusions based on the data and reports obtained, which are as follows:

1. Increase in production capacity:
 - Production capacity increased significantly, from 2618 decks per week to 3980 decks. This represents an improvement of approximately 52%, demonstrating the effectiveness of the implemented optimizations.
2. Reduction in cycle times:
 - The cycle time for work points was decreased. This allowed for a more efficient use of resources and an increase in the productivity of work points. The cycle time

was reduced by increasing the welding speed of the robotic cells and reducing the distances between the work points so that the operators could feed the work points faster.

3. Elimination of logistical blockages:
 - Replacing forklifts with conveyors eliminated bottlenecks and improved the material flow. Five of the six conveyors had a movement percentage of over 90%, indicating an optimized logistic flow.
4. Improving the degree of operation of robotic cells:
 - The optimizations reduced the waiting time and increased the operating percentage of the robotic cells. For example, the robotic welding cell OP2 reduced its waiting time from 44.822% to 35.77% and increased its uptime from 55.178% to 64.23%.
5. Streamlining the input flow of parts:
 - Decreasing the time of entry of parts into the flow allowed for an increase in the number of processed components. For example, for the bushing part, the input time was reduced from one minute to 0.7 min, increasing the number of parts processed from 6961 to 9943.
6. Reduction in waste:
 - Technological and functional optimizations also contributed to reducing the number of scraps. This aspect, although not detailed in the reports, is implicit in increasing production efficiency and quality.
7. Efficiency of workstations:
 - Reports indicate more efficient use of workstations, with increased uptime and reduced waiting time, thus contributing to higher productivity.
8. Reducing blockages in conveyors:
 - The only conveyor with significant bottlenecks was C6, suggesting that future optimizations may focus on this conveyor to completely eliminate bottlenecks.

The optimizations performed in the manufacturing architecture resulted in a significant increase in production capacity and operational efficiency. These improvements demonstrate the effectiveness of the optimization approach, both functionally and technologically. Detailed reports provide a solid basis for continuous monitoring and improvement in manufacturing processes in the future.

3.3. Mathematical Calculation for Maximizing the Profit by Optimizing the Logistic Flow Using the Simplex Method Mathematical

3.3.1. Simplex Method Description

The Simplex method is an approach to solving linear programming models by hand using slack variables, tableaus, and pivot variables as a means to finding the optimal solution to an optimization problem. A linear program is a method of achieving the best outcome given a maximum or minimum equation with linear constraints [18].

The optimization problem is a choice problem that involves a correction of entities called solutions/scenarios/variants. These solutions are compared and classified by a performance criterion.

There is the problem of finding the most appreciated solution called the optimal solution. The general study method of operational research can be schematized as follows:

- It starts from a real economic process;
- The study resulted in an optimization problem to which a mathematical model is attached;
- Once the model is obtained, we proceed to the identification of the solution method and the identification of the optimal solution [18,19].

3.3.2. Example of an Optimization Problem Solved with the Simplex Method

Three models of non-motor rear axle are proposed for manufacture: rigid non-motor axle, semi-rigid non-motor axle, and articulated non-motor axle. Taking into account that the automobile market is a developing one, it is desired that the diversity of a vehicle's features ensure the satisfaction of the majority of customers. The prices of the three types of bridges that will be manufactured are rigid non-motorized bridge—RON 850 (EUR 170), semi-rigid non-motorized bridge—RON 1000 lei (EUR 200), and articulated non-motorized bridge—RON 1720 (EUR 344).

The problem facing the manufacturing process is the supply sector, which is limited due to suppliers having capacity issues. Four of the component elements required for the production of the three types of axle have a limited monthly stock: link element (EDL), anti-roll bar, springs, and McPherson suspension.

To make a non-motorized rigid rear axle, we need the following:

- An EDL;
- An anti-roll bar;
- Two springs.

To make a non-motorized semi-rigid rear axle, we need the following:

- An EDL;
- An anti-roll bar;
- Two springs.

To make an articulated non-motorized rear axle, we need the following:

- An EDL;
- An anti-roll bar;
- Two springs;
- Two McPherson suspensions.

The monthly stock that suppliers can provide includes the following:

- EDL = 10,400 pieces;
- Anti-roll bar = 10,800 pieces;
- Springs = 19,900 pieces;
- McPherson suspension = 8000 pieces.

Thus, to maximize turnover, we need to determine how many decks should be made of each type, taking into account the constraints of available monthly inventory.

Answer:

We denote x_1 —the number of rigid non-motorized axles, x_2 —the number of semi-rigid non-motorized axles, x_3 —the number of articulated non-motorized axles, and z —the turnover.

With the restrictions

$$x_1 + x_2 + x_3 \leq 10,400 \quad (1)$$

$$x_1 + x_2 + x_3 \leq 10,800 \quad (2)$$

$$2x_1 + 2x_2 + 2x_3 \leq 19,900 \quad (3)$$

$$2x_3 \leq 8000 \quad (4)$$

$$x_1, x_2, x_3 \geq 0 \quad (5)$$

we convert the model to standard form as follows:

$$x_1 + x_2 + x_3 + y_1 = 10,400 \quad (6)$$

$$x_1 + x_2 + x_3 + y_2 = 10,800 \quad (7)$$

$$2x_1 + 2x_2 + 2x_3 + y_3 = 19,900 \quad (8)$$

$$2x_3 + y_4 = 8000 \quad (9)$$

Thus,

$$x_1 = x_2 = x_3 = 0 \quad (10)$$

and we have

$$y_1 = 10,400 \quad (11)$$

$$y_2 = 10,800 \quad (12)$$

$$y_3 = 19,900 \quad (13)$$

$$y_4 = 8000 \quad (14)$$

Now, all variables are positive:

$$x_1, x_2, x_3, y_1, y_2, y_3, y_4 \geq 0 \quad (15)$$

In Table 4, in the column highlighted in red, the basic variables are written. The coefficients of the objective function are written on the lines highlighted in green. In the column highlighted in blue, the free terms of the restrictions are written.

Table 4. The initial table.

	850	1000	1720	0	0	0	0		
	x_1	x_2	x_3	y_1	y_2	y_3	y_4		
y_1	1	1	1	1	0	0	0	10,400	0
y_2	1	1	1	0	1	0	0	10,800	0
y_3	2	2	2	0	0	1	0	19,900	0
y_4	0	0	2	0	0	0	1	8000	0
	−850	−1000	−1720	0	0	0	0	0	z

The initial solution is not optimal because there is at least one negative value. From the three negative solutions, we choose the one with the highest absolute value (i.e., 1720). The yellow column divides at the pivot (green column), i.e., $10,400:1 = 10,400$, $10,800:1 = 10,800$, $19,900:2 = 9950$, and $8000:2 = 4000$ (Table 5).

Table 5. Iteration no. 1—Stage 1.

	850	1000	1720	0	0	0	0		
	x_1	x_2	x_3	y_1	y_2	y_3	y_4		
y_1	1	1	1	1	0	0	0	10,400	0
y_2	1	1	1	0	1	0	0	10,800	0
y_3	2	2	2	0	0	1	0	19,900	0
y_4	0	0	2	0	0	0	1	8000	0
	−850	−1000	−1720	0	0	0	0	0	z

The smallest of these terms was chosen (i.e., $8000:2 = 4000$). The row (purple) containing the smallest element is the pivot row (Table 6).

Table 6. Iteration No. 1—Stage 2.

	850	1000	1720	0	0	0	0		
	x_1	x_2	x_3	y_1	y_2	y_3	y_4		
y_1	1	1	1	1	0	0	0	10,400	0
y_2	1	1	1	0	1	0	0	10,800	0
y_3	2	2	2	0	0	1	0	19,900	0
y_4	0	0	2	0	0	0	1	8000	0
	−850	−1000	−1720	0	0	0	0	0	z

The initial pivot line (y4) leaves the table.

Notably, y4 has left the table and x3 has entered (Table 7). With the input of x3, instead of 0 in the objective function, the coefficient of x3 will appear, i.e., 1720 (colored in pink).

Table 7. Iteration No. 1—Stage 3.

	850	1000	1720	0	0	0	0		
	x ₁	x ₂	x ₃	y ₁	y ₂	y ₃	y ₄		
y ₁	1	1	1	1	0	0	0	10,400	0
y ₂	1	1	1	0	1	0	0	10,800	0
y ₃	2	2	2	0	0	1	0	19,900	0
x ₃	0	0	2	0	0	0	1	8000	1720
	−850	−1000	−1720	0	0	0	0	0	z

The elements of the purple line are divided at the pivot, i.e., at 2.

In Table 8, the results after dividing the elements of the purple line at pivot 2 are shown.

Table 8. Iteration No. 1—Stage 4.

	850	1000	1720	0	0	0	0		
	x ₁	x ₂	x ₃	y ₁	y ₂	y ₃	y ₄		
y ₁	1	1	1	1	0	0	0	10,400	0
y ₂	1	1	1	0	1	0	0	10,800	0
y ₃	2	2	2	0	0	1	0	19,900	0
x ₃	0	0	2	0	0	0	1	8000	1720
	−850	−1000	−1720	0	0	0	0	0	z

The calculations in Equations (16)–(19) are the results of the arrows in Table 8 and are listed in Table 9 with each color corresponding to the arrow.

$$\frac{1 \cdot 2 - 0 \cdot 1}{2} = 1 \quad (16)$$

$$\frac{1 \cdot 2 - 0 \cdot 1}{2} = 1 \quad (17)$$

$$\frac{0 \cdot 2 - 1 \cdot 1}{2} = -0.5 \quad (18)$$

$$\frac{10400 \cdot 2 - 8000 \cdot 1}{2} = 6400 \quad (19)$$

$$6400 \cdot 0 + 6800 \cdot 0 + 11900 \cdot 0 + 4000 \cdot 1720 = 216000 \quad (20)$$

Table 9. Iteration No. 1—Stage 5.

	850	1000	1720	0	0	0	0		
	x ₁	x ₂	x ₃	y ₁	y ₂	y ₃	y ₄		
y ₁	1	1	0	1	0	0	−0.5	6400	0
y ₂	1	1	0	0	1	0	−0.5	6800	0
y ₃	2	2	0	0	0	1	−1	11,900	0
x ₃	0	0	1	0	0	0	0.5	4000	1720
	−850	−1000	0	0	0	0	860	6,880,000	z

Additionally, the same calculation method was used for the other cells (the number 2 below the fraction being the pivot).

In Table 9, in the pivot column, i.e., the column of x_3 , apart from element 1, which is the pivot, the rest of the column is padded with zeros.

Only the cells in the columns that are not colored are calculated.

If there are only numbers ≥ 0 in the last line, the calculation stops. If not, the previous calculation steps are repeated until there are only positive results.

Since there are still negative values, the procedure is repeated. From the two negative values, the column with the highest absolute value, i.e., 1000, is chosen.

The yellow column is divided by the pivot column (green column) ($6400:1 = 6400$, $6800:1 = 6800$, $11900:2 = 5950$, and $4000:0$ cannot be divided. The positive minimum is chosen). In this situation, y_3 leaves the column (since it is the minimum positive), and x_2 appears with a coefficient of 1000.

The purple row divides at the pivot, i.e., at 2, which is circled in Table 10 and passes the values in Table 11. After that, the calculations are performed for the other cells in the columns that are not colored, and they are also passed in Table 11. The calculations are performed as in Table 8, to which Equations (16) and (20) belong.

Table 10. Iteration No. 2—Stage 1.

	850	1000	1720	0	0	0	0		
	x_1	x_2	x_3	y_1	y_2	y_3	y_4		
y_1	1	1	0	1	0	0	−0.5	6400	0
y_2	1	1	0	0	1	0	−0.5	6800	0
y_3	2	2	0	0	0	1	−1	11,900	0
x_3	0	0	1	0	0	0	0.5	4000	1720
	−850	−1000	0	0	0	0	860	6,880,000	z

Table 11. Iteration No. 2—Stage 2.

	850	1000	1720	0	0	0	0		
	x_1	x_2	x_3	y_1	y_2	y_3	y_4		
y_1	0	0	0	1	0	−0.5	0	450	0
y_2	0	0	0	0	1	−0.5	0	850	0
x_2	1	1	0	0	0	0.5	−0.5	5950	1000
x_3	0	0	1	0	0	0	0.5	4000	1720
	150	0	0	0	0	500	360	12,830,000	z

Because there are no more negative values on the last row of Table 11, the calculation stops, and this solution is the optimal one.

From the calculation, it follows that in order to maximize the turnover, which is $z = \text{RON } 12,830,000$ (EUR 2,566,00), we must produce the following quantities:

$x_1 = 0$ (pieces)—Number of non-motorized rigid rear axles manufactured;

$x_2 = 5950$ (pieces)—Number of non-motorized semi-rigid rear axles manufactured;

$x_3 = 4000$ (pieces)—Number of articulated non-motorized rear axles manufactured;

$y_1 = 450$ (pieces)—The number of connecting elements (EDL) remaining after making the rear axles influenced by the stock constraints of the other components;

$y_2 = 850$ (pieces)—The number of anti-roll bars remaining after making the decks influenced by the stock constraints of the other components;

$y_3 = 0$ —The remaining number of springs;

$y_4 = 0$ —The remaining number of suspensions.

It is important to recognize that market conditions and component inventory availability may fluctuate. Thus, inventory management strategies and production planning should be flexible to respond to changes in demand and available resources.

The continuous monitoring of performance and adjustment of plans according to updated data and market feedback will ensure maintaining competitiveness and adaptability to changes in the business environment.

Market variables and fluctuations in the supply chain are a real risk in production because the market includes suppliers who cannot deal entirely with order variations. To avoid manufacturing risks, a minimum quantity is negotiated with the supplier, and a plan is made to recover the outstanding quantity. Due to the inability to comply with the orders, additional transport costs will be involved, as special transport will have to be organized to pick up the goods that are covered by the budget of the logistics department.

Another strategy to avoid risks in production is to schedule daily or weekly meetings in which the parts produced by the supplier are distributed so that none of his customers would be confronted with supply risks, and the production plan can be kept under observation until a solution to improve production is identified.

4. Conclusions

This paper leverages the advanced capabilities of the WITNESS Horizon simulation software to craft a virtual model of an automotive logistic flow. This digital twin of manufacturing architecture is a versatile tool that can assess various manufacturing scenarios and predict the evolution of performance parameters under changing conditions, such as worker fatigue, demand fluctuations, or equipment failures.

The virtual model was calibrated, comparing simulation output with actual production data to ensure the model accurately reflects real-world operations. In order to obtain improvements in production capacity and operational efficiency, the model was used to diagnose the performance indicator levels and identify the necessary changes. The focus was on identifying and validating the best parameters and the configuration of the manufacturing architecture. After using the virtual prototype to simulate the initial logistic flow, reports were generated, and the results obtained for each workstation were interpreted to identify the flow concentrators. The necessary changes to workstations were described, and the system architecture was modified accordingly. After these changes were implemented, detailed simulation results and optimization outputs (e.g., a 52% increase in production capacity, from 2618 to 3980 rear axles per week) were highlighted, demonstrating the significant impact of the optimization.

The Simplex method proved effective in solving the optimization problem of producing rear non-motorized axles, ensuring the identification of an optimal solution in a relatively small number of iterations. This demonstrates the utility and applicability of linear programming methods in production planning and optimization. The case study illustrated a complex process of optimizing production capacity and operational efficiency in an industrial environment. In conclusion, the case study demonstrates the success of a strategic and well-managed approach to optimizing industrial processes. Implementing changes and appropriate technologies leads to significant improvements in production capacity, operational efficiency, and logistics management, strengthening a company's position in the face of market challenges and ensuring a solid foundation for future growth. To improve operational performance, the model could be used to explore options for diversifying the product range, optimizing the supply chain, and evaluating the impact of new technologies to increase production efficiency. This research, by combining the virtual model functions with innovative strategies and advanced technologies, illustrates how significant results could be achieved in several key areas:

1. Improved production capacity: changes in the production architecture significantly increased production capacity from 2618 to 3980 rear axles per week, demonstrating effective optimization of existing processes.
2. Improved operational efficiency: the reduced cycle times at various workstations improved resource use and significantly enhanced overall operational efficiency in the production line.

3. Logistics optimization: a crucial part of the optimization process involved replacing forklifts with conveyors. This change eliminated logistics bottlenecks and enhanced the flow of materials, leading to improved synchronization of operations and overall logistics optimization.
4. Effective use of advanced technologies: the integration and improvement in robotic welding cells, which offer high-speed and high-precision welding, significantly reduced waiting times and increased operational efficiency in critical sectors. This is just one example of how advanced technologies can be effectively utilized to optimize processes.

The proposed virtual model shows significant improvements in both efficiency and flexibility; however, it has limitations, especially regarding scalability. These limitations must be addressed for further development of the model. As a result, future research will focus on conducting sensitivity analyses to evaluate how these optimizations perform under different conditions, thereby enhancing the system's adaptability to changing production demands. It will also track energy usage across robotic cells and conveyors to improve efficiency. Additionally, implementing real-world pilot studies will be crucial to validate the theoretical benefits and tackle any unforeseen operational challenges.

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References

1. Yousaf, M.U.; Aized, T.; Shabbir, A.; Ahmad, M.; Nabi, H.Z. Automobile rear axle housing design and production process improvement using Failure Mode and Effects Analysis (FMEA). *Eng. Fail. Anal.* **2023**, *154*, 107649. [\[CrossRef\]](#)
2. Liu, J.; Wang, D.; Lin, Q.; Deng, M. Risk assessment based on FMEA combining DEA and cloud model: A case application in robot-assisted rehabilitation. *Expert Syst. Appl.* **2023**, *214*, 119119. [\[CrossRef\]](#)
3. Ju, Y.; Zhao, Q.; Luis, M.; Liang, Y.; Dong, J.; Dong, P.; Giannakis, M. A novel framework for FMEA using evidential BWM and SMAA-MARCOS method. *Expert Syst. Appl.* **2024**, *243*, 122796. [\[CrossRef\]](#)
4. Pascual, A.I.; Högberg, D.; Lämkuill, D.; Luque, P.E.; Syberfeldt, A.; Hanson, L. Optimization of Productivity and Worker Well-Being by Using a Multi-Objective Optimization Framework. *IIE Trans. Occup. Ergon. Hum. Factors* **2021**, *9*, 143–153. [\[CrossRef\]](#) [\[PubMed\]](#)
5. Shao, S.; Murotsu, Y. Approach to failure mode analysis of large structures. *Probabilistic Eng. Mech.* **1999**, *14*, 169–177. [\[CrossRef\]](#)
6. Liu, H.-C.; Liu, L.; Liu, N. Risk evaluation approaches in failure mode and effects analysis: A literature review. *Expert Syst. Appl.* **2013**, *40*, 828–838. [\[CrossRef\]](#)
7. Larasari, P.A.; Tanaya, P.I.; Indrayadi, Y. Analysis and Improvement of Assembly Line: A Case Study at Automobile Rear-Axle Assembly Line-A PT. ZYX. *J. Ilm. Tek. Industri.* **2020**, *19*, 95–107. [\[CrossRef\]](#)
8. Eheim, M.; Kaiser, D.; Weil, R. On Automation Along the Automotive Wire Harness Value Chain. In *Advances in Automotive Production Technology—Theory and Application*, Proceedings of the Stuttgart Conference on Automotive Production (SCAP2020), ARENA2036. Stuttgart, Germany, 2–10 November 2020; Springer: Berlin/Heidelberg, Germany, 2021; pp. 178–186. [\[CrossRef\]](#)

9. Thelen, A.; Zhang, X.; Fink, O.; Lu, Y.; Ghosh, S.; Youn, B.D.; Todd, M.D.; Mahadevan, S.; Hu, C.; Hu, Z. A comprehensive review of digital twin—Part 1: Modeling and twinning enabling technologies. *Struct. Multidiscip. Optim.* **2022**, *65*, 354. [[CrossRef](#)]
10. Fabri, M.; Ramalhinho, H. Assessing the In-house Logistics flows in the automotive industry. *Comp. Ind. Eng.* **2024**, *187*, 109822. [[CrossRef](#)]
11. Yuan, B.; Lu, Y.; Wang, K.; Peng, X. Multi-objective optimization of the auto-carrier loading and routing problem in an automotive logistics company. *J. Oper. Res. Soc.* **2023**, *75*, 896–906. [[CrossRef](#)]
12. Wiecezorek, S.; Thies, C.; Weckenborg, C.; Grunewald, M.; Spengler, T.S. Volkswagen Group Logistics Applies Operations Research to Optimize Supplier Development. *INFORMS J. Appl. Anal.* **2023**, *54*, 147–161. [[CrossRef](#)]
13. Fabri, M.; Ramalhinho, H.; Oliver, M.; Muñoz, J.C. Internal logistics flow simulation: A case study in automotive industry. *J. Simul.* **2020**, *16*, 204–216. [[CrossRef](#)]
14. Li, X. Optimization of logistics flow management through big data analytics for sustainable development and environmental cycles. *Soft Comput.* **2024**, *28*, 2701–2717. [[CrossRef](#)]
15. Teplická, K.; Khouri, S.; Mudarri, T.; Freňáková, M. Improving the Quality of Automotive Components through the Effective Management of Complaints in Industry 4.0. *Appl. Sci.* **2023**, *13*, 8402. [[CrossRef](#)]
16. Science Direct, Rear Axles. Available online: <https://www.sciencedirect.com/topics/engineering/rear-axles> (accessed on 9 October 2024).
17. Tropimatica. Available online: <https://www.tropimatica.com/en/industries-automobile.php> (accessed on 9 October 2024).
18. Explanation of Simplex Method. Iowa State University. Available online: <https://www.imse.iastate.edu/files/2015/08/Explanation-of-Simplex-Method.docx> (accessed on 9 October 2024).
19. The Simplex Method—Stanford University. Available online: <https://stanford.edu/class/cme338/notes/notes06-simplex.pdf> (accessed on 9 October 2024).

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