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PhD thesis summary

OPTIMIZATION OF THE WIRING HARNESS ASSEMBLY FLOW IN THE AUTOMOTIVE INDUSTRY

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Introduction

The automotive industry is undergoing a major transformation driven by global trends such as electrification, active and passive safety, and the integration of connectivity and infotainment functions. All these factors lead to a considerable increase in the complexity of electrical wiring harnesses, which have become extensive systems with thousands of connections, tens of kilograms of wires, and hundreds of components. In this context, the wiring harness is no longer just a passive assembly but a strategic element for the operation of the modern vehicle.

However, wiring harness production remains one of the most human-dependent sectors in the automotive industry. Despite increased automation in other areas, wiring harness assembly lines still rely over 80% on manual work due to the low flexibility of components and the complexity of insertion, bundling, and fastening operations. This dependency generates challenges such as: large variability in work time between operators, idle times in material supply, handling errors, and difficulties in standardizing quality.

These challenges overlap with constraints imposed by the industry: strict delivery deadlines, high diversity of harness references, limited factory space, and continuous pressure for cost reduction. In addition, requirements related to traceability and sustainability demand that logistics and assembly processes be not only efficient but also transparent and compatible with circular economy principles.

The motivation for this research stems from the need to find integrated solutions for increasing wiring harness line productivity, reducing bottlenecks, eliminating idle times, and digitalizing logistics flows. The approach combines traditional line-optimization methods (task balancing, flow reorganization) with modern digital solutions (RFID for automated inventory, Witness simulation for scenario testing) and perspectives for partial or full automation of critical processes.

The general objective of the thesis is to increase productivity and flexibility in wiring harness production through:

i. optimizing the distribution of operations across workstations,
ii. introducing a new assembly line architecture,
iii. integrating RFID technology for storage and automated inventory, and
iv. defining a methodological framework for the automation of flexible components.

This objective is supported by a set of working hypotheses tested through case studies and simulations.

The working hypotheses of the thesis are formulated as follows:

1) redistributing operations across workstations and balancing tasks lead to the elimination of bottlenecks and an increase in productivity;
2) the hybrid architecture (dynamic line + carousel) enables the reduction of idle times and the stabilization of takt time;
3) RFID technology, implemented at warehouse level, ensures automatic inventory and full traceability;
4) automation-oriented design rules and the classification of flexible components can increase the degree of automation in assembly processes.

The expected contributions of the research are both theoretical and practical. From a theoretical perspective, the work develops a mathematical optimization model for the assembly flow (linear programming, duality, complementary slackness) and proposes a classification of flexible components based on criteria relevant to automation. From a practical perspective, the thesis validates a new line architecture through Witness simulations, describes a complete model for RFID implementation in wiring harness warehouses, and demonstrates through an advanced pilot (automatic insertion of fuses/relays) the applicability of the Digital Twin concept.

The structure of the thesis is organized to reflect the logical stages of the research and the obtained results:

Chapter 1 presents the evolution of the automotive industry and the transformation of wiring harness production, with emphasis on current trends and development directions.

Chapter 2 analyzes the specific characteristics of wiring harnesses and the challenges associated with organizing assembly lines, including the impact of the high share of manual labor on productivity.

Chapter 3 details perspectives on automating the wiring harness assembly flow, highlighting their particular characteristics and the analysis of automation potential.

Chapter 4 addresses the integration of RFID technology in logistics processes and proposes solutions for automated inventory.

Chapter 5 proposes a new wiring harness assembly line structure and validates its optimization potential through simulations in Witness Horizon Software.

Chapter 6 proposes the automation of fuse insertion into fuse and relay boxes, using Digital Twin concepts and robotics.

Chapter 7 includes the general conclusions and summarizes the original contributions of the research.

Through this structure, the thesis aims to provide both the theoretical foundation and the practical demonstration of the applicability of the proposed solutions, contributing to the development of a scientific and technological framework for optimizing electrical wiring harness production in the automotive industry.

Chapter 1. Evoluția industriei auto și transformarea producției de cablaje electrice

The introductory chapter analyzes the evolution of the automotive industry from the perspective of the technological, organizational, and architectural transformations that have directly influenced the production of electrical wiring harnesses. The automotive industry is presented as a dynamic field, continuously adapting to innovations, regulations, and changes in consumer behavior. Over more than a century of development, automotive production has evolved from craftsmanship to globalized and digitalized systems, while electrical wiring harnesses—initially simple assemblies of a few wires—have become complex infrastructures that interconnect thousands of vehicle functions.

The chapter follows the evolution of wiring harnesses in parallel with the stages of the automotive industry: the first minimally equipped vehicles, the introduction of mass production, the rise of comfort and safety features, the integration of electronics, and finally the transition toward the digital vehicle. The increasing complexity of wiring harnesses has driven both the standardization of components and processes, as well as the need to make production more flexible. Although full automation is still limited by the nature of the materials, critical operations such as cutting, stripping, or crimping have been highly automated.

An important emphasis is placed on the evolution of production organization: from artisanal methods to Taylorism and assembly lines, and later to the implementation of lean principles and ISO/IATF standards, all in the context of relocating production to low-cost regions. The current organizational model relies on a combination of skilled manual labor and selective automation.

The chapter also addresses the transformation of the vehicle's electrical architecture: from point-to-point connections, to modular structures with ECUs, then to distributed networks, and today to zonal architectures that support the software-defined vehicle. The evolution of electric vehicles has introduced high-voltage wiring harnesses, with strict requirements for insulation, safety, and thermal management.

Finally, the chapter presents current trends: digital twin and Industry 4.0, automation through collaborative robots, advanced standardization, the use of lightweight materials, the integration of automotive Ethernet, sustainability, and the shift toward smart wiring harnesses. These directions anticipate a profound transformation of harness manufacturing, in which digitalization, modularity, and efficiency become central elements.

Chapter 2. The current state of research in the automation of wiring harness assembly processes in the automotive industry

Chapter 2 analyzes the complexity of automotive wiring harnesses and how it impacts the feasibility of automating assembly flows. The growing number of electrical and electronic functions has led to a massive diversification of wiring harnesses, which now include thousands of components and dozens of different processes. Examples such as the Audi A8 or the Mercedes-Benz OM654 engine harness illustrate the high degree of structural and functional complexity found in modern products.

The design process of a wiring harness requires close collaboration between electrical engineering teams and mechanical engineering teams. Specialized software tools (e.g., Capital, Catia, LDorado) are used to define the harness architecture, routing paths, and interconnections. Numerous constraints must be considered: available space, mechanical tolerances, total weight, electromagnetic compatibility, and safety requirements. At this stage, component identification codes, testing plans, and integration procedures within the vehicle are also defined.

The production process of wiring harnesses includes several stages. The first stage is the preparation of prefabricated elements: cutting wires to precise lengths, stripping the ends, applying terminals through crimping, inserting seals, and marking the wires for traceability. Equipment such as Komax Alpha or Zeta partially automates these operations, reducing quality variations. After wire preparation, the prefabricated elements are stored. This is a critical step because wires and connectors must be organized into batches and delivered to the assembly lines in exact quantities and on time. Insufficient control can lead to delays and line stoppages.

The chapter describes the main types of assembly lines used in the industry: LAD dynamic lines, employed for modules and small-sized harnesses, and carousel-type lines, used for complex and large-scale products. The choice of line type has a direct impact on ergonomics, internal logistics, and the possibilities for automation.

Major difficulties in fully automating the process are highlighted: the flexibility of the wires, the wide variety of components, the diversity of operations (crimping, ultrasonic welding, connector insertion, application of protective elements), the high number of

variants, and the need for rapid adaptation to design changes. These limitations explain why wiring harness production remains significantly dependent on manual operation.

An important part of the chapter is dedicated to the wiring harness design process, which includes defining the electrical schematic, selecting wire diameters, protective elements, and connectors based on their position within the vehicle, analyzing electromagnetic interference, and performing 3D modeling required to validate routing and avoid contact with harsh or hard-to-reach areas. Based on the 3D model, 2D assembly boards used in production are created.

The chapter then details the stages of the production process: preparation of prefabricated elements (the stage with the highest level of automation), storage in the picking area, and testing of representative samples. Modern equipment such as Komax Alpha automatic crimping machines, twisting/crimping machines, and ultrasonic welding systems are presented, highlighting their role in increasing productivity and quality.

The LAD assembly flow is analyzed in detail, including the method of supplying workstations, the sequence of operations, and 100% electrical testing of the products. Verification procedures are described (continuity, sealing, presence and conformity of accessories), as well as the challenges of manual rework, which significantly impact production times.

The LAD (dynamic assembly line) technology is one of the established solutions in the wiring-harness industry. Its advantage is that tasks can be divided sequentially and synchronized, reducing handling times. However, the challenges lie in balancing the workload across stations and ensuring a smooth logistical supply.

An unbalanced flow may lead to excessive accumulation in one buffer and shortages at other stations, disrupting the overall rhythm of the line. Therefore, modeling and simulating this flow are essential for identifying bottlenecks and testing optimization scenarios.

A preliminary case study was conducted using the Witness Horizon software. The model included 13 workstations, 9 buffers, and 19 operators. The results showed excessive build-ups after station 4 and progressively increasing idle times for the operators at the end of the line. Three optimization hypotheses were tested:

(I) reducing working times,

(II) shortening feeding times, and

(III) redistributing operations and reducing the number of operators.

Only the third hypothesis led to unblocking the flow, significantly increasing per-shift productivity and equalizing occupation rates.

The conclusion of this chapter is that manual or semi-automated assembly lines face structural limitations, and the solution does not lie solely in accelerating individual processes, but in intelligently redistributing tasks and reorganizing the overall flow. These results justify exploring hybrid architectures and integrating supportive digital technologies such as simulation and RFID-based traceability, which will be detailed in the following chapters.

Chapter 3. Perspectives on Automating the Wiring Harness Assembly Flow in the Automotive Industry

Automation of the automotive wiring-harness assembly flow is a strategic priority for the industry, driven by the need to increase productivity, reduce dependence on manual labor, and ensure consistent quality. Currently, over 80% of operations remain manual, especially those involving flexible components, which limits production throughput and increases costs.

A first level of automation is represented by Komax Zeta 640/650 equipment. These machines enable full processing of electrical wires: cutting, stripping, terminal crimping, seal insertion, inkjet marking, and quality checks (pull-test, crimp-force monitoring). The system can handle up to 36 different wire types, offering a high level of flexibility for mixed production batches. The major advantage is the reduction of human errors and shorter preparation times.

At a higher level, Komax Omega 745/755 equipment automates complex operations such as simultaneous insertion of wires into multipolar connectors, seal application, and lever closing. Force and angle-controlled movements ensure insertion precision even for miniaturized components, extending automation into areas previously inaccessible. These machines deliver significant gains in quality consistency but require substantial investment and careful calibration.

The APA (Automation Potential Analysis) methodology, developed by Fraunhofer IPA, proposes a systematic framework for evaluating the automation potential of each operation. Every sequence—separation, handling, positioning, and joining—is assessed through technical and economic indicators, and the results allow classification of processes as fully automatable, partially automatable, or non-automatable.

Human–robot collaboration will play an important role in the future. Collaborative robots (cobots) can take over repetitive tasks or ergonomically demanding activities (such as

lifting components or performing preliminary positioning), allowing human operators to complete operations requiring fine dexterity or visual adaptation. However, handling flexible components such as electrical wires remains a technical challenge, as these components do not retain their shape and deform easily.

The thesis proposes a classification of flexible components according to several criteria: basic shape (cubic, flat, elongated), symmetry, rigidity (KBs coefficient), supply format (bulk, reels), and possible deformation types. This classification makes it possible to identify areas where automation is feasible and those where redesign is required.

In addition, a specific indicator is introduced—the p_{cvm} index (the probability that the Position/Control/View/Manipulate movements can be automated). This index was applied to the "Position" and "Release" movements, showing that through redesign of certain components, the automation potential increases from ~54% to ~93%. For example, replacing a flexible strap with a rigid clip simplified handling and enabled the use of a standardized gripper.

The design recommendations formulated focus on adapting components for robotic manipulation: adding rigid gripping zones, limiting unwanted degrees of freedom, adding visual markers for optical recognition, and standardizing dimensions. These rules facilitate future robot integration and reduce automation costs.

The conclusion of this chapter is that the future of wiring-harness automation will combine high-performance specialized equipment, analysis methodologies (APA), component redesign, and human–robot collaboration. This creates the foundation for integrating Digital Twin solutions and for moving gradually from manual production to assisted production and, in the long term, to near-full automation.

Chapter 4. Use of RFID Technology in Wiring-Harness Component Storage Systems

The accelerated transformations in the automotive sector—pressure for decarbonization, intensifying global competition, and demand volatility—require component suppliers to achieve sustained increases in productivity and traceability. In this context, component warehouses become a strategic link: they ensure the timely availability of materials, maintain quality integrity, and provide resilience to supply-chain disruptions. Warehouse automation through modern technologies (WMS, RFID, Voice/Light Picking, AS/RS) can reduce handling errors, speed up receiving processes, provide real-time inventory, and enable automatic replenishment mechanisms, especially when supplier–customer systems are interconnected. RFID stands out as a key technology thanks to contactless identification, simultaneous reading of multiple tags, and easy integration into complex logistical flows.

Although the reliability of modern technologies is proven, adoption remains uneven. A survey conducted among Slovenian automotive-industry suppliers shows a persistent preference for traditional solutions (barcodes) over RFID or Voice/Light Picking—an indication of uneven technological maturity and investment constraints. Although this observation is local, it provides a useful indication of perceived barriers in Central and Eastern Europe.

RFID (Radio Frequency Identification) technology provides a high-performance alternative to traditional barcodes. Unlike barcodes, RFID tags do not require direct line-of-sight and allow the simultaneous reading of dozens or even hundreds of tags. There are three main categories: LF (125–134 kHz), HF (13.56 MHz), and UHF (860–960 MHz). For logistics applications, UHF is preferred due to its long reading distance (up to several meters) and high reading speed.

The RFID architecture includes readers (fixed/mobile), antennas, tags, and a software component (server + middleware) that collects, filters, and distributes data to the organization’s applications. Tags cover a broad technological spectrum: LF (short-range, robust in harsh environments), HF (access control/cards), UHF (warehousing, supply chain—typical range 3–8 m), and SHF for special applications. From an energy-management perspective, passive tags (battery-less) offer the best cost–benefit ratio, semi-passive tags

extend reading distance through a dedicated battery for their logic, and active tags provide long autonomy/long-distance reading for high-value or mobile assets.

RFID (Radio Frequency Identification) technology provides a high-performance alternative to traditional barcodes. Unlike barcodes, RFID tags do not require direct visual contact and allow the simultaneous reading of dozens or even hundreds of tags. There are three main categories: LF (125–134 kHz), HF (13.56 MHz), and UHF (860–960 MHz). For logistics applications, UHF is preferred due to its long reading distance (up to several meters) and high reading speed.

The proposed model structures the warehouse into four interconnected zones, supporting a logistics flow with high variability (products, packaging, versions, production urgencies). The control points are:

- Receiving: pallets pass through RFID portals; tags are read automatically, data is validated and associated with a route or storage location; HMI screens can display the “optimal path” to the rack.
- Storage: forklifts equipped with an RFID kit (passive/active readers, antennas, mini-PC, LED signal tower, and pallet optical sensor) pick up pallets, transport them to the assigned locations, and scan the rack tags to automatically associate or de-associate goods from locations.
- Picking area: sub-packages are sorted and re-labeled hierarchically (pallet → level-1 subunits → level-2), so that the system accurately reflects the content of each container and enables fast allocation to production orders.
- Internal shipment to production: the exit portal reads the volume and identity of items, updates stock levels in real time, and the middleware publishes events to the applications.

“RFID pucks”—active tags placed in key zones—add a localization dimension: when a forklift approaches, they activate and transmit their position (LF for precise activation, UHF for data transmission). By correlating portal logs, mobile readings, and puck signals, the system can reconstruct actual routes, detecting deviations, delays, or potential issues.

A central element of the model is the standardization of labeling:

- UHF passive tags for low cost and compatibility with high-volume flows;
- Tags on pallets and on sub-units, with hierarchical links in the system (pallet ↔ level 1 ↔ level 2);

- Rules for tag placement (location, height, orientation) and pallet-loading methods to ensure optimal radio visibility;
- Contractual requirements for suppliers: deliveries must arrive already tagged, reducing re-labeling workload and minimizing non-conformity risks at receiving.

The proposed RFID system architecture includes fixed readers installed at the warehouse's entry and exit points, RFID portals through which component containers pass, RFID-equipped forklifts, RFID tags ("pucks") attached to strategic rack locations, and a middleware software system connected to the ERP database. This architecture enables automatic identification of every container and full traceability of its movements.

The proposed conceptual model for implementing RFID technology describes in detail the configuration of the RFID portal: a master column equipped with an industrial mini-PC, a 12" HMI screen, a UHF reader, directional antennas, a multi-protocol RFID module, an Ethernet switch, a passage detector, and an LED signal tower for visual feedback; a slave column extends the field strength and coverage. All components operate at 24 V, are industrial-grade (IP protection, temperature, vibration resistance), and integrate industrial Ethernet protocols. The model also describes the configuration of the RFID kits installed on the forklifts.

The key functionalities of this system are:

(i) (i) automatic association of containers with production orders,

(ii) (ii) de-association once they are unloaded on the line,

(iii) (iii) automatic routing of containers to the appropriate sections, and

(iv) (iv) instant inventory of the entire warehouse through a simple database query.

Even though the "real-time" stock level is derived from current RFID events, periodic inventory is still necessary for validation and calibration. The material presents several options: handheld readers, tele-guided vehicles, or fixed readers mounted on ceilings/shelves, all relying on distance estimation using RSSI. Advanced localization approaches based on SAR (Synthetic Aperture Radar) adapted for RFID are also discussed, comparing SAR-WA (single-trajectory) and MT-SAR (multi-trajectory); the latter achieves superior accuracy (2–4 cm) in experiments conducted with a mobile robot in a controlled warehouse environment.

The conceptual model proposes an all-wheel-drive UGV (for stability, servo braking, adequate autonomy, and IP protection), equipped with a UHF reader, four compact RAIN RFID antennas, and a mini-PC, enabling autonomous inventory operations. The recommended workflow includes: an implementation phase (laser mapping, route definition,

MT-SAR reference readings, interference calibration) and an operational phase (periodic scanning rounds, event export to the middleware, and automatic reconciliation in the WMS/ERP).

To validate the applicability of RFID technology for automatic inventory processes in the warehouse of an automotive wiring-harness manufacturer, experimental measurements were carried out focusing on the characterization of the reading field, determination of hysteresis limits, and analysis of how performance depends on tag distance and orientation. The objectives of the experiment were to identify the optimal reading zones of the RFID antenna—by delimiting stable regions and dead zones—analyze the hysteresis phenomenon for single and multiple tags to understand signal persistence and its impact on inventory accuracy and evaluate the influence of tag orientation on detection range and reliability.

- Reading-field mapping shows an optimal entry zone within approximately X ≈ 80–100 cm and Y ≈ ±30 cm (with the antenna at the origin), but also reveals "islands" and "holes" typical of UHF radiation. Once the first reading is established, detection can be maintained even very close to the antenna (~5 cm), highlighting operational hysteresis: the entry threshold is more restrictive than the hold threshold. Practical implication: object trajectories must be aligned with the "acquisition corridor," and discontinuities can be compensated with additional antennas or angle adjustments.
- Hysteresis – single tag: the central area (X = 30–60 cm) offers predictability (differences of 1–2 cm between entry/exit); at the extremities (X ≥ 90 cm), hysteresis increases (up to ~4.5 cm), especially on the negative Y direction, reflecting field asymmetry and possible reflections.
- Hysteresis – multiple tags (packed subunits): at larger distances, hysteresis amplifies (up to ~9 cm at X ≈ 97 cm), with pronounced asymmetry on negative Y due to shielding/reflections caused by complex packaging. Conclusion: the optimal zone for passing packed boxes is the proximal-central area (X = 5–45 cm), where thresholds are clear and stable.
- Distance and orientation (Y = 0): performance strongly depends on angle. Angles of 30°–60° yield the best ranges (up to 80–90 cm), 180° remains stable up to ~75 cm, while 90° is unfavorable (readability only 5–15 cm). Implication: standardizing tag orientation and guiding flows through zones with stable field geometry are critical for robustness.

These results validate the idea that the performance of an RFID system is the outcome of the interaction between field geometry, hysteresis, the number and orientation of tags, and packaging characteristics.

Mobile solutions for inventory operations add flexibility. An autonomous guided vehicle (UGV) equipped with an RFID reader can navigate the warehouse and perform a full inventory without interrupting activities. In large warehouses, drones equipped with RFID antennas can fly over the racks, reducing inventory time from several days to just a few hours.

The benefits of implementing RFID are numerous: a significant reduction in inventory errors, complete traceability of components, digital integration of the logistics flow with assembly lines, and the elimination of the need for manual inventory. In addition, RFID provides real-time data, which facilitates production planning and resource optimization.

The conclusion of this chapter is that RFID is not merely an identification technology but a strategic tool for warehouse digitalization and their integration into the Industry 4.0 paradigm. Its implementation creates the foundation for fully connected systems in which logistics and production flows are monitored and optimized in real time.

Chapter 5. Optimization of the Logistics Flow for Wiring-Harness Assembly Through the Introduction of a New Assembly-Line Structure

The initial structure of the assembly line analyzed in the study includes 13 workstations, 9 buffers, and 19 operators. In the baseline configuration, the production flow faced significant bottlenecks, especially after station 4, where the accumulation of semi-finished products caused delays and major imbalances. Operators at the end of the line experienced long idle periods, while others were overloaded, indicating an inefficient distribution of tasks.

In this context, three optimization hypotheses were formulated. The first hypothesis targeted reducing working times by increasing the individual productivity of operators. The second hypothesis focused on reducing feeding times through better logistical coordination and shorter supply routes. The third hypothesis proposed redistributing operations between workstations and reducing the number of operators. Simulation results showed that only the

third hypothesis led to a real improvement, eliminating bottlenecks and increasing productivity.

Based on these results, a new line architecture was proposed— a hybrid structure combining the advantages of a LAD (dynamic assembly) line with those of a carousel. The new line is organized into two identical sides, each supplied symmetrically, allowing for a more balanced distribution of tasks and a significant reduction in buffer accumulations.

Simulations performed in Witness Horizon confirmed the validity of the proposed architecture. The parametric model showed a productivity increase of approximately 12%, with the line being able to produce 296 harnesses in two shifts, compared to 264 in the initial configuration. The takt time decreased from 6.80 minutes to 6.08 minutes, reflecting improved synchronization of operations.

Analysis of operator utilization rates showed a much more balanced distribution of tasks, with reduced idle times and the elimination of overload at certain stations. In addition, transit times between buffers were reduced, and excessive accumulations were eliminated. This resulted in greater flow stability and an overall higher yield.

A central element of the research was the integration of a mathematical optimization model based on linear programming. The objective function aimed to maximize productivity by minimizing workstation processing times, under the constraint that their sum must not exceed the imposed takt time. The model used the Simplex algorithm, and the dual analysis made it possible to interpret shadow prices to identify critical stations.

The use of duality theory and complementary slackness also contributed to validating the simulation results. This approach demonstrated that the obtained solution is not only locally optimal, but also mathematically robust. The connection between the simulation model and the mathematical model provided a complete framework for analyzing and validating the proposed architecture.

The partial conclusion of this chapter is that the new hybrid LAD + carousel architecture ensures a significant increase in productivity, better task balancing, and a reduction in idle times. Validation through both simulations and mathematical models strengthens the robustness of the proposal. These results create the foundation for extending towards the implementation of a Digital Twin and for integrating advanced automation solutions into the assembly flow.

The production of electrical wiring harnesses generates significant amounts of waste, both in the form of wire and cable scraps and rejected connectors, defective terminals, or unusable insulating materials. In the context of increasingly strict European regulations

regarding the circular economy and environmental protection, the management of this waste is no longer only a legal obligation but also an opportunity to reduce costs and strengthen sustainability.

The types of waste resulting from production processes include:

(i) scraps of copper or aluminum wires,

(ii) defective parts such as connectors or fuses,

(iii) residues of insulating materials, particularly PVC and HFFR (Halogen-Free Flame Retardant) or LSZH (Low Smoke Zero Halogen) compounds.

A portion of this waste can be recycled through mechanical processes, while others require chemical or thermal treatments.

To support recycling, selective collection must be organized directly in the production area. In this regard, collection points should be integrated into the assembly-line layout, and operators must be trained to sort wire scraps, rejected connectors, and plastic materials into separate containers. The use of RFID tags for waste traceability is an innovative solution that enables monitoring of quantities and their movement.

Recycling methods are diverse. Mechanical shredding and electrostatic separation are commonly used solutions for separating metallic conductors from insulating materials. Thus, copper and aluminum can be recovered and reintegrated into industrial circuits. In the case of HFFR-based insulating materials, research has shown that $Mg(OH)_2$, the main flame-retardant component, can be recovered through chemical treatments and reintegrated into new compounds.

Another direction is pyrolysis, whereby plastic materials undergo controlled thermal processes to produce fuels or secondary raw materials. This method has the advantage of energy recovery from waste but requires significant investment and strict emissions control. Experimental studies cited in the literature show that through shredding and electrostatic separation, a metal-recovery rate of over 95% can be achieved, making these processes economically attractive. Moreover, reintegrating recycled plastic materials reduces dependence on primary resources and contributes to companies' sustainability objectives.

The conclusion of this chapter is that waste recycling in wiring-harness production should be seen not only as a compliance requirement with environmental regulations but as an integral part of logistics-flow optimization and economic competitiveness. Through selective collection, digital traceability, and the application of modern recycling methods, costs can be reduced, sustainability can be increased, and the wiring-harness industry can align with circular-economy principles.

Chapter 6. Optimization of Fuse Assembly in Fuse and Relay Boxes Using API Technology for Digital Twin

Although wiring-harness production benefits from certain forms of automation, many operations remain manual, especially those involving miniaturized components. Fuse insertion is a critical stage that can generate defects difficult to detect in later tests: incorrect angle, insufficient pressing force, imperfect electrical contact, or component damage. The study proposes a flexible robotic solution that addresses these issues through precise control of angle and force. Correct assembly of fuses and relays in automotive fuse boxes is a critical process, as any error can lead to major vehicle malfunctions and high repair or recall costs. Traditional processes, based on manual visual inspection, are prone to human error and provide limited traceability.

The specialized literature includes attempts at partial automation such as wire-handling with sensor-equipped robots, automated routing processes, systems for cable covering, or automated electrical testing. However, several areas remain uncovered by industrial solutions, one of which is fuse assembly—still performed manually in most factories.

The characteristics of fuses and the insertion requirements specified by manufacturers are analyzed: a perpendicular 90° angle, correct alignment with the contacts, force limits (below 40–55 N depending on the fuse type), and the need to avoid oblique insertions that lead to imperfect contacts. To prevent such errors, some manufacturers recommend the use of guiding masks.

The proposed solution integrates the Ufactory Lite 6 collaborative robot, configured and calibrated through the definition of Denavit–Hartenberg parameters and the use of transformation matrices for precise end-effector positioning. The rigorous kinematics, combined with its 0.5 mm repeatability, enables the robot to perform fine operations such as handling and inserting fragile components.

The methodology includes three major stages:

1) Creation of the Digital Twin model – using Onshape and API technology to generate a virtual replica of the fuse box; this model enables operation simulation, extraction of the exact coordinates of insertion positions, and real-time monitoring.

2) Configuration and integration of the robot – calibration of the 3D-printed gripper, definition of the initial position, programming of movements in Python using the xArm API, connection with the Digital Twin, and data synchronization.
3) Integration of computer vision – using OpenCV and DepthAI for detecting fuses based on shape and color and for validating their presence in the box. Artificial vision helps compensate for positional variations of the fuse box without requiring a fixed template.

The proof of concept (POC) confirms the feasibility of digital integration:

- 3D models of the fuses and the box were created through reverse engineering.
- The gripper was designed to securely hold the fuses without causing damage.
- Virtual connectors were added to the CAD model to determine the precise coordinates of each insertion location.
- Vision algorithms enabled identification of the type and position of the fuses in the storage area.
- The insertion sequence was optimized to avoid errors: approach, positioning 2 mm above the slot, rotation, and controlled perpendicular insertion.

The experimental tests confirmed the system's performance:

- 99.5% accuracy in fuse insertion, superior to manual processes.
- Fine force control, eliminating issues associated with insufficient or excessive force in human operation.
- High flexibility, with the system adapting to small dimensional variations in fuse boxes or fuses.
- Operational reliability, with the robot functioning without major errors during repeated cycles.
- Results validated through multiple test cycles and statistical analysis (mean, standard deviation). The main limitation identified is the use of an educational-grade robot; for industrial applications, specialized robots with higher precision and speed are recommended.

The conclusions highlight the major contributions of the research:

• the introduction of a completely new solution for automating fuse insertion, a process that has so far remained non-automated in the industry;
• the establishment of a methodological framework in which the digital twin not only simulates but directly controls the physical process through real-time feedback;
• the demonstration of a scalable model that can be extended to other critical manual-assembly processes in the automotive industry;
• the direct contribution to the development of smart manufacturing and the Industry 4.0 paradigm, through the integration of robotics, artificial vision, and digital twin technologies.

Chapter 7. Final Conclusions and Main Contributions to the Optimization of the Wiring-Harness Assembly Flow in the Automotive Industry

1. General Conclusions

The thesis has achieved its stated objectives, demonstrating that the optimization of the automotive wiring-harness assembly flow can be accomplished through an integrated approach that combines line reorganization, the use of digital technologies, and a commitment to sustainability.

The analysis of the current state highlighted the strong dependency on human labor and the vulnerabilities of manual and semi-automated lines.

Automation perspectives showed that Komax equipment, the APA methodology, and human–robot collaboration open promising directions, provided that flexible components are redesigned.

The integration of RFID in warehousing proved to be an effective solution for automatic inventory, traceability, and connectivity with ERP systems.

The new hybrid LAD + carousel line architecture, validated through Witness simulations and linear-programming mathematical models, demonstrated a productivity increase of 12% and a reduction of takt time from 6.80 to 6.08 minutes.

The sustainability study showed that recycling is not only a legal requirement but also an opportunity to reduce costs and integrate circular-economy principles.

2. Original Contributions

- Definition of an integrated methodology for optimizing the wiring-harness assembly flow, combining current-state analysis, software simulations, mathematical models for task redistribution, and the integration of digital technologies (RFID, Digital Twin).
- Proposal and validation of a new assembly-line structure, capable of reducing production bottlenecks and increasing productivity, confirmed through simulations and comparative analyses between the initial and the proposed configuration. The new assembly-line structure led to a 12% productivity increase and a reduction of takt time from 6.80 to 6.08 minutes.
- Introduction of a new component-storage structure to facilitate RFID integration into logistics systems, with impact on traceability, inventory accuracy, and the efficiency of supply flows.
- Development of solutions for the collection and recycling of waste generated by wiring-harness production, aligned with sustainability objectives and the reduction of environmental impact.

- Contribution to the development of a methodology for applying the Digital Twin concept to wiring-harness production, with emphasis on real-time monitoring and dynamic adjustment of industrial processes. By using API technology for connecting the Digital Twin to fuse-assembly processes, an insertion accuracy of over 99.5% was achieved.
- Contribution to the advancement of smart-manufacturing and Industry 4.0 concepts, opening new perspectives for applying these technologies to other complex manual-assembly processes.
- Identification of current automation limitations and formulation of future research directions aimed at increasing the integration of human-robot collaboration and developing adaptive optimization algorithms.

3. Limitations of the Research

- The experimental validation was carried out on a single industrial case (engine-harness line for the K9K).
- The simulations were predominantly deterministic, without incorporating stochastic variations to reflect uncertainty in real production environments.
- Full automation of the flow remains limited by the high cost of equipment and by the availability of components redesigned for robotic manipulation.
- The impact on human resources (training, reskilling) was not analyzed in detail within this thesis.

Bibliography

[1] Olbrich S., Lackinger Julia., Manufacturing Processes of automotive high-voltage wire harnesses: State
of the art, current challenges and fields of action to reach a higher level of automation, Procedia CIRP 107 (2022) 653–660, DOI: 10.1016/j.procir.2022.05.041.

[2] Lorenz N., Mayer R., Approaches for automated wiring harness manufacturing: function integration with additive manufacturing, Automotive and Engine Technology (2023) 8:227–237/ Springer, 2023, DOI: https://doi.org/10.1007/s41104-023-00137-9.

[3] Rosa, E. S., Godina R., Rodrigues E.M.G., Matias J.C.O., An Industry 4.0 Conceptual Model Proposal for Cable Harness Testing Equipement Industry, Procedia Computer Science 200 (2022) 1392–1401, DOI: 10.1016/j.procs.2022.01.340.

[4] Guerrero R., Serrano-Hernandez A., Pascual J., Faulin J., Simulation Model for Wire Harness Design in the Car Production Line Optimization Using the SimPy Library, Sustainability (2022), 14, 7212, DOI: https://doi.org/10.3390/su14127212.

[5] Wang H., Björn J., Deep Learning-Based Connector Detection for Robotized Assembly of Automotive Wire Harnesses, 2023 IEEE 19th International Conference on Automation Science and Engineering (2023), DOI: 10.1109/CASE56687.2023.10260619.

[6] Burkacky O., Deichmann J., Stein J.P., Automotive software and electronics 2030: Mapping the sector's future landscape, https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/mapping-the-automotive-software-and-electronics-landscape-through-2030 (accesare la 25.08.2025)

[7] International Energy Agency (IEA), Global EV Outlook 2022, IEA Report, 2022

[8] Trommnau J., Kühnle J., Siegert J., Inderka R., Bauernhansl T., Overview of the State of the Art in the Production Process of Automotive Wire Harnesses, Current Research and Future Trends, Procedia CIRP. 81. 387-392 (2019), DOI: 10.1016/j.procir.2019.03.067.

[9] ***, Poză linie de asamblare cablaj, https://jobs.diez.md/articles/o-fabrica-de-cablaje-auto-din-cahul-va-angaja-circa-1500-de-persoane-pana-in-toamna-anului-viitor (accesare la 16.01.2021)

[10] ***, Poză linie de asamblare cablaj, https://timponline.ro/trei-detectivi-mercedes-benz-bistrita-descoperit/ (accesare la 14.01.2021)

[11] Warnecke H.J., Walther J., Schlaich G. (1985), Flexible Automated Wiring Harness Assembly, In: Bullinger, HJ., Warnecke, H.J. (eds) Toward the Factory of the Future. Springer, Berlin, Heidelberg, 453–460 (1985), DOI: https://doi.org/10.1007/978-3-642-82580-4_76

[12] **Stefan (Iorga) Ioana,** Popescu C.A., Popa C.L., Coteț C.E., Research regarding assembly flow optimization of wiring harness in automotive industry, MATEC Web of Conferences 343:02003 (2021), DOI: 10.1051/matecconf/202134302003.

[13]***, Harness the full potential of wiring systems, https://www.leoni-wiring-systems.com/ (accesare la 11.10.2020)

[14]***, Test procedures, https://www.leoni-machinery-sensors.com/en/about-us/quality/test-procedures/, (accesare la 04.10.2020)

[15]***, Harness manufacturing, https://www.komaxgroup.com/en/products/wire-processing/higher-automation-platforms/harness-manufacturing, (accesare la 20.12.2020)

[16]***, Analysis of automation potentials in assembly processes, https://www.ipa.fraunhofer.de/en/expertise/robot-and-assistive-systems/assembly-automation/analysis-of-automation-potentials-in-assembly-processes.html, (accesare la 10.08.2021)

[17] Trommnau J., A.N., Limp Component Design for Automatic Assembly - Classification Ratting System and Design Rules, 53rd CIRP Conference on Manufacturing Systems 1139 - 1144. Procedia CIRP 93 (2020), DOI: 10.1016/j.procir.2019.03.067.
[18] Trommnau J., A.F., Design for Automatic Assembly: A new Approach to Classify Limp Components. CIRP Design 2020 49 - 54. Procedia CIRP 91(2020)
[19] Škerlič S., Muha R., Sokolovskij E., Application of modern warehouse technology in the Slovenian automotive industry, Transport, Vol. 32, no. 4, (2017), 415–425.
[20] Popescu A., Enciu G., Popescu Emilia, Tache Irina, Architecture of the RFID systems used in production systems, Proceedings in Manufacturing Systems, Vol. 12, Issue 4, (2017), pp. 155–160.
[21] Naija Y., Secured Digital Architectures for Low Cost Full-fledged HF RFID Tags, National Engineering School of Sousse (2018).
[22] Junhong M., Research on Intelligent Warehouse Management System Based on RFID, Proceedings of the 2020 9th International Conference on Applied Science, Engineering and Technology (ICASET 2020), Atlantis Press, 29–32,(2020).
[23] ***, RFID Systems, https://www.ia.omron.com/support/guide/47/introduction.html (accesare la 21.03.2021)
[24] Lindsay J.D., Reade W., Cascading RFID Tags, https://www.jefflindsay.com/rfid3.shtml (accesare la 21.03.2021)
[25] **Stefan (Iorga) Ioana**., Popescu A.C., Popa C.L., Dobrescu T.G., Cotet C.E., The usage of RFID technology in wiring component storage systems. Proc. Manuf. Syst. 2021, 16, 109–116, (2021)
[26] ***, RFID Middleware Introduction, https://rfid4u.com/rfid-middleware-introduction (accesare la 12.05.2021)
[27] Choojan T., Chutima P., Part Transportation Improvement in Warehouse of an Automotive Factory, IOP Conference Series: Materials Science and Engineering, Vol. 131, No. 1, IOP Publishing, 1–7, (2016)
[28] ***, IER SAS, Solution D'identification Kit Rfid Pour Chariot Élévateur (Rfid Kit Identification Solution For Forklift Truck), https://market.ier.com/464-kit-rfid-pour-chariot-elevateur.html, (accesare la 10.05.2021)
[29]***, IER SAS, Solution D'identification Totem Rfid (Totem Rfid Identification Solution), https://market.ier.com/451-totem-rfid.html, (accesare la 10.05.2021)
[30] R. O'Byrne, Solution D'identification Warehouse Design – Rules of Thumb… And a Checklist, https://www.logisticsbureau.com/warehouse-design-rules-of-thumb, (accesare la 12.05.2021)
[31] ***, Zebra Technologies, FX9600 Fixed RFID Reader Support, https://www.zebra.com/us/en/support-downloads/rfid/rfid-readers/fx9600.html#knowledgearticlesear, (accesare la 14.05.2021)
[32] ***, AtlasRFIDstore, Kathrein Wide Range 30° RFID Antenna (FCC/ETSI), https://www.atlasrfidstore.com/kathrein-wide-range-30-rfid-antenna-fcc-etsi, (accesare la 14.05.2021)
[33] ***, Advantech Co, WA-HT3120T, https://www.advantech.com/products/ff03268d-575b-4fe0-83b8-3add57792b9d/wa-ht3120t/mod_e1ce4106-8966-4a18-8b01-dd94a53ee0e8, (accesare la 14.05.2021)
[34] ***, Turck Group, TBEN-LL-4RFID-8DXP RFID Interface, https://www.turck.de/attachment/100013753.pdf, (accesare la 10.05.2021)
[35] ***, WERMA Signaltechnik, Completely pre-assembled Signal Towers, https://www.werma.com/en/s_c1505i2610/K37_plug_EM_Pulse_tone_24VAC/DC_GN/YE/RD/69921075.html, (accesare la 08.11.2021)
[36] ***, MTI Wireless Edge Ltd, Circular Antennas, https://www.mtiwe.com/?CategoryID=278&ArticleID=284, (accesare la 12.05.2021)

[37] ***, Impinj, Impinj Speedway RAIN RFID Readers for Flexible Solution Development, https://www.impinj.com/products/readers/impinj-speedway, (accesare la 12.05.2021)
[38] ***, Panasonic Corporation of North America, Adjustable Range Reflective Photoelectric Sensor Amplifier Built-in EQ-30 SERIES, https://b2b-api.panasonic.eu/file_stream/pids/fileversion/2292, (accesare la 12.05.2021)
[39] ***, ELA Innovation, Sciel Reader Ip2 / Wf2, https://elainnovation.com/wp-content/uploads/2021/01/FP-SCIEL-READER-IP2-WF2-05B-EN-2.pdf, (accesare la 12.05.2021)
[40] ***, ELA Innovation, Active DOT RFID Tag Activator, https://elainnovation.com/wp-content/uploads/2021/01/FP-TAG-ACTIVATOR-02C-EN.pdf, (accesare la 12.05.2021)
[41]***, ELA Innovation, PUCK DOT User Guide, https://elainnovation.com/en/catalogue/puck-dot-en, (accesare la 12.05.2021)
[42] Svub J., Stasa P., Benes F., Vojtech L., Neruda M., et al.., Autonomous System for UHF RFID Signal Measurement in Industrial Environment, 11th IFIP Wirelessand Mobile Networking Conference (WMNC2018), 81-86., hal-01995443, (2018)
[43] Bernardini F., Motron A., Nepa P., Buffi, Alice, Tellini B., SAR-based Localization of UHF-RFID Tags in Smart Warehouses, Conference: 2020 5th International Conference on Smart and Sustainable Technologies,1-6, DOI: 10.23919/SpliTech49282.2020.9243755 (2020)
[44]***, AgileX Robotics SCOUT 2.0, https://global.agilex.ai/products/scout-2-0, (accesare la 22.05.2021)
[45] **Iorga, Ioana**, Popa, C. L., Popescu, C.-A., Chiscop, Florina, Dobrescu, T. G., Cotet, C. E., Automatic Inventory of Wiring Harness Components Using UHF RFID Technology. Logistics, 10(2), 33, (2026) https://doi.org/10.3390/logistics10020033
[46] Popa, C.L., **Iorga, Ioana,** Cotet, C.E., Ifrim, Ana Maria, Popescu, C.-A., Dobrescu, T.G., Optimization of Wiring Harness Logistics Flow in the Automotive Industry. Appl. Sci. 2024,14, 10636, (2024), DOI: https://doi.org/10.3390/app142210636
[47] Fernandes, M.M., de Almeida, I.A., Junior, H.M. Automotive Miniaturization Trend: Challenges for Wiring Harness Manufacturing; Technical Report; SAE Technical Paper: Warrendale, PA, USA, 2010.
[48] Rius Rueda, A. A Novel Optimisation Methodology of Modular Wiring Harnesses in Modern Vehicles: Weight Reduction and Safe Operation; Universitat Politècnica de Catalunya: Barcelona, Spain, 2017.
[49] Beloglazov, I., Krylov, K. An Interval-Simplex Approach to Determine Technological Parameters from Experimental Data.Mathematics 2022, 10, 2959.
[50] Vagaská, A., Gombár, M., Straka, L'. Selected Mathematical Optimisation Methods for Solving Problems of Engineering Practice.Energies 2022, 15, 2205.
[51] Syifa, E.A., Istiqomah, T.N., Puspita, N.P., Ratnasari, L., Khabibah, S., Anggoro, P.W., Bawono, B. The application of linear programming for the optimal profit of pt. Maruna using the simplex method. Manag. Syst. Prod. Eng. 2023, 31, 138–143.
[52] Galankashi, M.R., Helmi, S.A., Hashemzahi, P. Supplier selection in automobile industry: A mixed balanced scorecard–fuzzy AHP approach. Alex. Eng. J. 2016, 55, 93–100.
[53] Wang, Q.Z., Chen, J.M., Tseng, M.L., Luan, H.M., Ali, M.H. Modelling green multimodal transport route performance with witness simulation software. J. Clean. Prod. 2020, 248, 119245.
[54] Wenjing, L., Shichang, L. Optimization of Automotive Wire Harness Production Process Based on Lean Manufacturing. In Proceedings of the 2nd International Conference on Engineering Management and Information Science, EMIS 2023, Chengdu, China, 24–26 February 2023.
[55] Heisler, P., Utsch, D., Kuhn, M., Franke, J. Optimisation of wire harness assembly using human–robot-collaboration. Procedia CIRP 2021, 97, 260–265.

[56] Palomba, I., Gualtieri, L., Rojas, R., Rauch, E., Vidoni, R., Ghedin, A. Mechatronic Redesign of a Manual AssemblyWorkstation into a Collaborative One for Wire Harness Assemblies. Robotics 2021
[57] Salunkhe, O., Stahre, J., Romero, D., Li, D., Johansson, B. Specifying Task Allocation in Automotive Wire Harness Assembly Stations for Human-Robot Collaboration. Comp. Ind. Eng. 2023, 184, 109572.
[58] Szajna, A., Stryjski, R., Woźniak,W., Chamier-Gliszczyński, N., Kostrzewski, M. Assessment of Augmented Reality in Manual Wiring Production Process with Use of Mobile AR Glasses. Sensors 2020, 20, 4755
[59] Bi, Z.; Pomalaza-Ráez, C., Hershberger, D., Dawson, J., Lehman, A., Yurek, J., Ball, J. Automation of Electrical Cable Harnesses Testing. Robotics 2018, 7, 1.
[60] Yang, F., Wang, P., Zhang, R., Xing, S., Wang, Z., Li, M., Fang, Q. A*–Ant Colony Optimization Algorithm for Multi-Branch Wire Harness Layout Planning. Electronics 2024, 13, 529.
[61] Nguyen, H.G., Habiboglu, R., Franke, J. Enabling deep learning using synthetic data: A case study for the automotive wiring harness manufacturing. Procedia CIRP 2022, 107, 1263–1268.
[62] Song, J., Kumar, P., Kim, Y., Kim, H.S. A Fault Detection System for Wiring Harness Manufacturing Using Artificial Intelligence. Mathematics 2024, 12, 537.
[63] Yamano, Y., Hosokawa, T., Hirai, H., Ono, J., Otsuka, T., Tabata, M.; Otsuka, Y., Nishikawa, T., Kitamura, S., Yoshimoto, J., Development of the aluminium wiring harness. SEI Tech. Rev. 2011, 73–80.
[64] Wedrychowicz, M., Kurowiak, J., Skrzekut, T., Noga, P. Recycling of Electrical Cables—Current Challenges and Future Prospects. Materials 2023, 16, 6632.
[65] Blinová, Lenka, Godovcin, P. Importance of Recycling the Waste-Cables Containing Copper and PVC. Res. Pap. Fac. Mater. Sci. Technol. Slovak Univ. Technol. 2021, 29, 1–21.
[66] Zackrisson, M. Recycling Production Cable Waste-Environmental and Economic Implications; WASTES: Solutions, Treatments and Opportunities; 2nd International Conference; CVR—Centre for Waste Valorization: Braga, Portugal, 2013.
[67] Czarnecka-Komorowska, D., Kanciak,W., Barczewski, M., Barczewski, R., Regulski, R., Sedziak, D., Jedryczka, C. Recycling of Plastics from Cable Waste from Automotive Industry in Poland as an Approach to the Circular Economy. Polymers 2021, 13, 3845.
[68] Zackrisson, M., Jönsson, C., Olsson, E. Life Cycle Assessment and Life Cycle Cost ofWaste Management—Plastic CableWaste. Adv. Chem. Eng. Sci. 2014, 4, 1–12.
[69] Jebbor, I., Benmamoun, Z., Hachimi, H., Raouf, Y., Haqqi, M., Akikiz, M. Improvement of an Assembly Line in the Automotive Industry: A case study in wiring harness assembly line. ICIEA 2023, 35, 62–71.
[70] Lakhal,W. Etude, Mise en Place et Amélioration de L'efficience de Processus de Montage de Câblage Au Sein de LEONI; Diplôme National d'Ingénieur en Génie Electromécanique, École Nationale d'Ingénieurs de Sfax: Sfax, Tunisia, 2019
[71] Ruppert, T., Abonyi, J. Software Sensor for Activity-Time Monitoring and Fault Detection in Production Lines. Sensors 2018, 18, 2346.
[72] Katsumata, M., Suzuki, H. Method For Recycling Waste Wire Harness. U.S. Patent US20030115989A1, 15 February 2005. pp. 1–5.
[73] Arslan, F., Arslan, C. Recycling of waste electrical cables. Mater. Sci. Eng. Int. J. 2019, 3, 107–111.
[74] Cazacu, Carmen-Cristiana., **Iorga, Ioana**., Parpală, R.C., Popa, C.L., Cotet, , C.E. Optimizing Assembly in Wiring Boxes Using API Technology for Digital Twin. Appl. Sci. 2024, 14, 9483. DOI: https://doi.org/10.3390/app14209483
[75] ***, T.E., instruction sheet:crfb, 36 miniature fuses ("cabin relay and fusebox"), https://www.te.com/commerce/DocumentDelivery/DDEController?Action=srchrtrv&DocNm=408-

15007&DocType=Specification%20Or%20Standard&DocLang=English&DocFormat=pdf&PartCntxt=1801764-1, (accesare la 09.02.2024).
[76] Eheim, M., Kaiser, D., Weil, R. On Automation Along the Automotive Wire Harness Value Chain. In Advances in Automotive Production Technology—Theory and Application; Weißgraeber, P., Heieck, F., Ackermann, C., Eds.; ARENA2036; Springer: Berlin/Heidelberg, Germany, 2021; pp. 178–186.
[77] Govoni, A., Laudante, G., Mirto, M., Natale, C., Pirozzi, S. Towards the Automation of Wire Harness Manufacturing: A Robotic Manipulator with Sensorized Fingers. In Proceedings of the 9th International Conference on Control, Decision and Information Technologies (CoDIT), Rome, Italy, 3–6 July 2023.
[78] Heisler, P., Steinmetz, P., Yoo, I.S., Franke, J. Automatization of the Cable-Routing-Process within the Automated Production of Wiring Systems. Appl. Mech. Mater. 2017, 871, 186–192.
[79] Heisler, P., Kuhn, M., SüßWolf, R., Franke, J. Innovative Solutions for the Covering Process in the Manufacturing of Wire Harnesses to Increase the Automation Degre. In Proceedings of the IEEE 11th International Conference on Mechanical and Intelligent Manufacturing Technologies (ICMIMT), Cape Town, South Africa, 20–22 January 2020.
[80] Navas-Reascos, G., Romero, D., Stahre, J., Caballero-Riuz, A. Wire Harness Assembly Process Supported by Collaborative Robots: Literature Review and Call for R&D. Robotics 2022, 11, 65
[81] Román-Ibáñez, V., Pujol, F.A. Collaborative robotics in wire harnesses spot taping process. Comput. Ind. 2021, 125, 103370.
[82] 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.
[83] Garg, G., Kuts, V., Anbarjafari, G. Digital Twin for FANUC Robots: Industrial Robot Programming and Simulation Using Virtual Reality. Sustainability 2021, 13, 10336.
[84] Barricelli, B.R., Casiraghi, E., Fogli, D. A Survey on Digital Twin: Definitions, Characteristics, Applications, and Design Implications. IEEE Access 2019, 7, 167653–167671.
[85] Erdei, T.I., Krakó, R., Husi, G. Design of a Digital Twin Training Centre for an Industrial Robot Arm. Appl. Sci. 2022, 12, 8862
[86] Popescu, D., Dragomir, M., Popescu, S., Dragomir, D. Building Better Digital Twins for Production Systems by Incorporating Environmental Related Functions—Literature Analysis and Determining Alternatives. Appl. Sci. 2022, 12, 8857.
[87] Iliută, Miruna-Elena, Moisescu, M.A.; Pop, E.; Ionită, Anca-Daniela, Caramihai, Simona-Iuliana, Mitulescu, T.C. Digital Twin—A Review of the Evolution from Concept to Technology and Its Analytical Perspectives on Applications in Various Fields. Appl. Sci. 2024, 14, 5454.
[88]***,Ufactory Lite 6—User Manual V2.0.0., https://www.ufactory.cc/wp-content/uploads/2023/05/Lite6-User-Manual-V2.0.0.pdf, (accesare la 03.02.2024).
[89]***,Ufactory Lite 6—DH Parameters, https://www.ufactory.cc/wp-content/uploads/2023/04/Kinematic-and-Dynamic-Parameters-of-UFACTORY-Lite-6.pdf (accesare la 03.02.2024).
[90] Modi, P.P., Sunny, M.S.H., Khan, M.M.R., Ahmed, H.U., Rahman, M.H. Interactive IIoT-based 5DOF Robotic Arm for Upper Limb Telerehabilitation. IEEE Access 2022, 10, 114919–114928
[91]***, Onshape Digital Twins|Digital Transformation in Education, https://ptc-education.github.io/docs/solutions/onshapedx (accesare la 04.02.2024).
[92]***, Swe-Check−Blade Fuse Sizes., https://www.swe-check.com.au/editorials/blade_fuse_sizes.php (accesare la 15.02.2024).

[93]***, Onshape−Mate Connectors., https://cad.onshape.com/help/Content/mateconnector.htm (accesare la 04.03.2024).