

Research regarding assembly flow optimization of wiring harness in automotive industry

Ioana Stefan (Iorga)¹, Adrian Constantin Popescu¹, Cicerone Laurentiu Popa^{1,}, Tiberiu Gabriel Dobrescu¹, and Costel Emil Cotet¹*

¹University Politehnica of Bucharest, Robots and Production System Department, 313 Splaiul Independentei, Bucharest, Romania

Abstract. Considering the strong need for improvement of security and multimedia systems in the automotive industry, wiring harness production is becoming more and more important. Adapting to the integration of new technologies on the vehicle is a challenge for wiring harnesses manufacturers. Now the production of wiring harnesses is still quite dependent on human resources, the way of distributing the workload on the workstations having a large share in increasing productivity. Components such as terminals, connectors and seals are getting smaller and smaller, making the manual handling more difficult. A solution to this problem could be increasing the automation degree in wiring harness production. The objective of the research topic approached in this article is to identify solutions for optimizing the wiring assembly flow by partially automating the production flow. The concern for the application of automated processes in the production of car wiring is not new, but so far, the wiring manufacturers have been more focused on automating the prefabrication of the elements that compose the harness and not the wiring harness assembly line. From an economic point of view, the automation of the assembly flow would increase productivity by reducing fabrication time and the uncertainty given by the human resource dependence.

1 Introduction

Due to the characteristics and the functions it performs, the wiring occupies a unique place in the architecture of the vehicle. With a share of approximately 95% of the price of the harness being represented by manual preparation/assembly operations, the automation of harness production is a field that has aroused the interest of both researchers and wiring harness manufacturers.

2 Current state of automation of harness assembly flow

In automotive industry, the harness is a set of components (wires, terminals, connectors, seals, protections, fasteners, grommets, fuses, relays, fuses and relays boxes etc.) that

*Corresponding author: laur.popa79@gmail.com

ensure the connection between electrical and electronic components integrated into the vehicle.

Harness diversity has increased simultaneously with the vehicle evolution in terms of electrical and electronic functionality, integration of new communication technologies, control and software applications in the options available when purchasing a vehicle.

This fact has led to the augmentation of the complexity and therefore the weight that the wiring harnesses occupies in the weight of the vehicle. For example, in the case of an Audi A8 (version 2018) the wiring harnesses weighs 36 kg and put together the wires that are part of the harnesses would stretch for several kilometers. A useful example to illustrate the complexity of the wiring harness is given by a version of the engine harness of a Mercedes-Benz OM654 which contains: 54 connectors, 116 wires, has when stretched a length of 4 m² and a weight of 1.5 kg.[1]

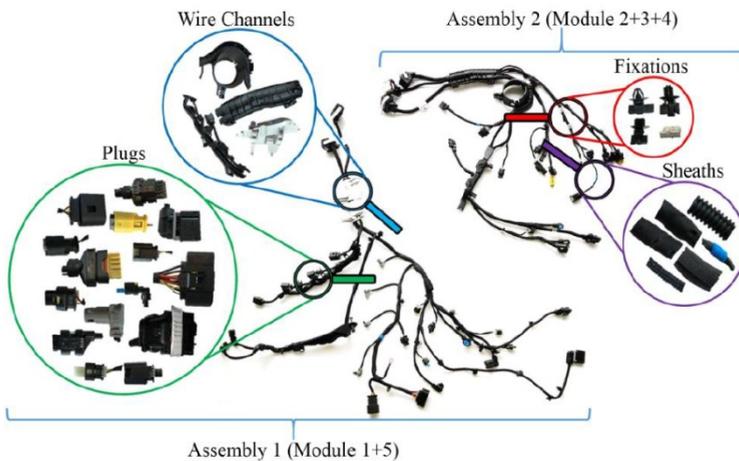


Fig. 1. Mercedes-Benz OM654 Engine Harness and Variant Diversity of Selected Components. [1]

Due to the complexity of wiring harnesses and their diversity, the wiring manufacturers have two choices:

- either to divide the wiring into smaller modules (where possible), manufactured on dedicated assembly lines for each module, the final assembly of the wiring being made later (within the same production site or at a site located in the proximity of the car manufacturer),
- or to manufacture the final wiring on larger and more complex assembly lines.

But regardless of their choice, the manufacture of the modules and the final assembly requires the same manufacturing and assembly technologies.

The production flow is organized according to the implemented assembly technology, which usually is structured into:

- Dynamic assembly line: usually used for the manufacturing of harness modules and smaller harnesses. There are several types of dynamic assembly lines developed, but the most common one used for the manufacturing of less complex harnesses is composed of fixed assembly boards (trays), with a conveyor belt placed in the inferior part of the line, used to carry the harness from one workstation to another. The line is organized so the components to use for assembly are provided frontally, ensuring the ergonomics of the of the workstations. [2]
- Carousels (also known as a rotary) for the manufacture of large modules and for the final assembly of modules. A carousel is composed of several boards mounted on a rail so that it

can turn. This production technology is often used to break down all work into several basic tasks. The assembly line consists of several boards, where each operator performs a limited number of operations assigned to his workstation, which are always the same, before rotating / moving the carousel. The pace of the line is established so it can ensure both productivity and quality standards.

Regardless of whether the manufacturer chooses to assemble the wiring using a dynamic assembly line(LAD) or a carousel assembly line, in order to supply it, workstations and equipment are needed to produce the preassembled elements that are part of the final wiring.

Automating the assembly flow is a challenge for wiring harness manufacturers. The automated harness assembly system must be very flexible and easily adaptable to meet the diverse and dynamic requirements that arise during the various stages of the project.

Difficulties in automating the wiring harness assembly flow:

- Difficulty in handling since the wires that are part of the harness are very flexible elements and have long lengths [3]
- Large variety of components that form the final harness: wires of different lengths and diameters, terminals, seals, connectors, protections, connecting parts, fasteners, etc. [3]
- Diversity of operations necessary to ensure connectivity: simple crimping (manual or automatic), double wire crimping (manual or automatic), ultrasonic welding, twisting, insertion of terminal-wire assembly in the connector, application of protections, etc. [3]
- The diversity of the harnesses produced within a project, many references that require different assembly boards (trays).
- Changes to the wiring architecture that occur during the development phase of the project, which involves the rapid modification / adaptation of the order of operations and the assembly system
- Changes imposed by after-sale quality incidents, although smaller than in the development phase, also involve rapid adaptation of the wiring assembly system

3The electrical wiring harness design process

The design process for wiring harnesses must consider several factors that allow the optimal integration of the harness into the vehicle architecture. A harness is expected to function at the same parameters, without altering the connection between the elements for approximately 20 years, so the design process must ensure the quality and the reliability of the product.[1] For this to be possible, the design process must consider the quality of the parts that compose the harness and the materials from which they are made (which must not contain prohibited substances in the countries where the product is to be marketed or about which is known that it will become banned in the coming years).

The design of the harness begins with the realization of the electrical wiring diagram, which includes all electrical and electronic equipment, as well as the electrical connections between them. Depending on their operating requirements, important technical aspects are established by electrical study, such as:

- the diameter of the wires required to ensure an optimal connection
- the caliber (rating) of the fuses that will protect the wires
- caliber of relays
- it is decided to use twisted wires instead of unitary wires to eliminate electromagnetic interference where appropriate

The wiring architecture will be done considering the temperature and humidity constraints imposed by the area in which they are integrated on the vehicle, therefore:

- the components of the wiring must have a temperature class corresponding to the environment in which they will operate,
- in areas of the vehicle prone to high humidity, the use of sealed connectors and seals in the crimping of the metal terminal on each the wire is required,
- the choice of the protections applied on the wires will be made according to the aggressive potential of the area through which the wiring passes and to the flexibility requirements imposed by the assembly,
- for the optimal protection, orientation and fixing of the wiring, connecting parts will be used (protective grommets for wires when passing through a metal frame, plastic parts for fixing and forming a path, etc.).

An especially important step in the design process is the 3D modelling of the harness, which helps define how it will be integrated into the vehicle. In the 3D model are represented all the components that are part of the environment in which the wiring will operate. This is the phase in which the harness path is established, and the harness debate is simulated in order to predict and prevent future incidents caused by the aggression of the harness if it is in contact with other parts. The wiring path must comply with several conditions, such as:

- elimination of the risk given by the proximity with elements / areas with aggressive potential by using the corresponding fixing elements and the protections imposed by the existing thermal regime in the area through which the harness passes,
- the chosen path must be as direct as possible, so as not to increase the length of the wiring more than necessary,
- the choice of the path must consider the need to make the harness assembly on the vehicle as easy as possible. If the difficulties of mounting the wiring on the vehicle are ascertained, it requires the modification of the path and / or the modification of the wiring harness architecture (modification of the length of the wiring drifts, elimination or addition of fixing elements).

Any deviation from the above conditions will result in changes to the wiring that depending on the stage of the project, it generates higher or lower costs.

Based on the electrical diagram and 3D modelling, a 2D drawing is made which is drawn on the wiring assembly board [1]. For the carousel type assembly lines, the 2D drawing contains the full layout of the harness, with indications essential for the harness assembly. Each board that enters the component of the assembly line has the same drawing marked on it. For the type of dynamic assembly line most used in practice, several 2D drawings are elaborated, corresponding to the specific phase of the assembly process, made on each board that composes the assembly line.

4 The electrical wiring harness production process

Beside the final assembly of the harness, the production process includes many phases necessary for the obtaining the product, each with a different degree of automation. These are mainly divided in:

- The production of preassembled elements,
- Storing the preassembled elements and the other components needed for the final assembly of the harness in a dedicated space, generally called the picking zone,
- Testing representative samples at the beginning of each production cycle [6].

In order to obtain an overview of how automation is applied today in wiring harness production, these phases are to be detailed in this article.

4.1 The production of preassembled elements

This is the phase with the highest degree of automation in harness production. The production section of preassembled elements is situated apart but in the proximity of the harness assembly line. It is structured in manual, semiautomated and fully automated workstations, as it will be detailed in the following part of the article.

Semiautomated workstation for removing wire insulation: this type of workstation is composed by an operator and a semiautomated wire stripping machine used for micro-coaxial cables involving especially tough precision requirements. It performs operations such as: full stripping, half stripping, multi-step stripping, coaxial and triaxial cable processing, coaxial and triaxial cable processing (detailed in the image below).



Fig. 2. Example of semiautomated stripping machine and performed operations [4]

Fully automated twisting and crimping machines: these machines work with highly precision, and they are used for performing specific operations on wires with long length and reduced cross section. The automated twisting and crimping machines mostly used by harness manufacturers have a modular composition, making it more adaptable to production requirements. As described in the image below, they can do various tasks such as: wire cutting, insulation removal, seal insertion, crimping, twisting.

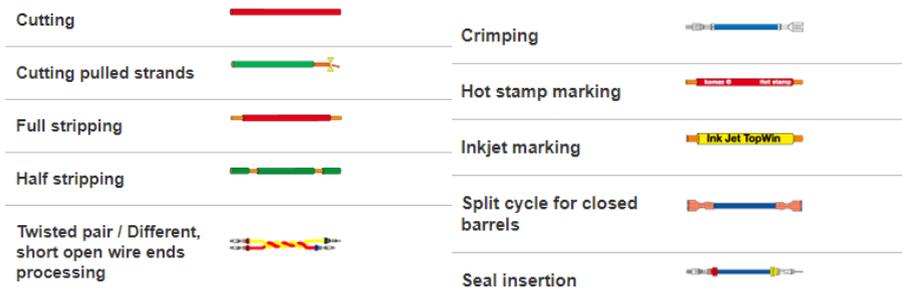


Fig. 3. Example of operations made with a twisting/crimping machine [4]

The integration of fully automated crimping machines in the production of preassembled elements has led to an important increase of the productivity, simultaneously with cost reduction. Capable of handling long wire lengths, these machines are used for a wide range of functions, including double crimping (crimping two wires on a single terminal) [5,10]

Even if automated machines for ultrasonic welding do exist, in practice making a wiring harness requires many types of splices that cannot be performed in a fully automated

process. This is the main reason for which ultrasonic welding is still realized by an operator using an ultrasonic welding machine.

Workstations for heat shrink tubes insertion: the heat shrink tubes are applied on the wires usually to protect splices and crimping areas (especially on larger cross section wires). This type of workstation is less complex than the other, the operations to be made are quite simple, but must be done with care to avoid damaging the appliance zone. The operator inserts the tube on the wire/splice and holds it on top of a hot air blower machine, while rotating the assembly to distribute heat evenly.

4.2 Component and preassembled elements testing phase

Before validating the use of the components that will be part of the harness, manufacturers perform tests necessary to establish if a component meets the quality standards required or not. The testing is made in the test center, an area especially designed to this purpose, where the endurance test to various aggressive factors is made for wires, splices, and crimped terminal-wire ensemble. [5, 9]

Types of test performed in the test center:

- Drag chain test,
- Torsional stress test,
- Bending test,
- Flame test,
- Media resistant test.

At the beginning of each production cycle, representative samples for splices (ultrasonic welding) and crimped terminal-wire ensemble are being submitted to endurance tests and micrographic quality check in order to ensure that the parameters set for the semiautomated and fully automated machines are in accordance with the required quality standard.

4.3 Harness production on a dynamic assembly line

The way in which the automated and the manual processes are combined within the production of the wiring harness, can be highlighted in the structure of a dynamic assembly line. The harness assembly line has a low degree of automation, being serviced by operators that effectuate various manual operations, such as:

- orientation of the wires according to the drawing printed on the assembly board,
- insertion of terminals in connectors,
- taping and applying protections according to the drawing printed on the assembly board.

Each assembly workstation is composed of:

- Fixed assembly boards on which the components are assembled, the structure of each board changes according to the operations for which it was designed,
- The component storage area is organized so the components to use for assembly are provided frontally, and is periodically supplied by an operator,
- Conveyor belt situated below the assembly board, used to transport the harness branches from one workstation to another [7, 8].

After completing the assembly process, all harnesses are tested. This is done with the help of the electrical test and control table which is specially designed to correspond to the architecture of the harness to be tested. Because connectors are not allowed to be connected during this test, the test table is equipped with special devices that touch the metal terminals in the connector sockets without using the connection mechanism. Checking the wiring involves performing several types of tests:

- electrical test, for checking wiring continuity,

- air pressure leakage test, to check the waterproofness for components that must meet this requirement,
- an integrity test and verification of the levers / secondary locking mechanisms by using devices specially designed for each connector that has a system for ensuring the connection by secondary closing,
- conformity verification test according to the electrical diagram to check the presence of fuses and relays.

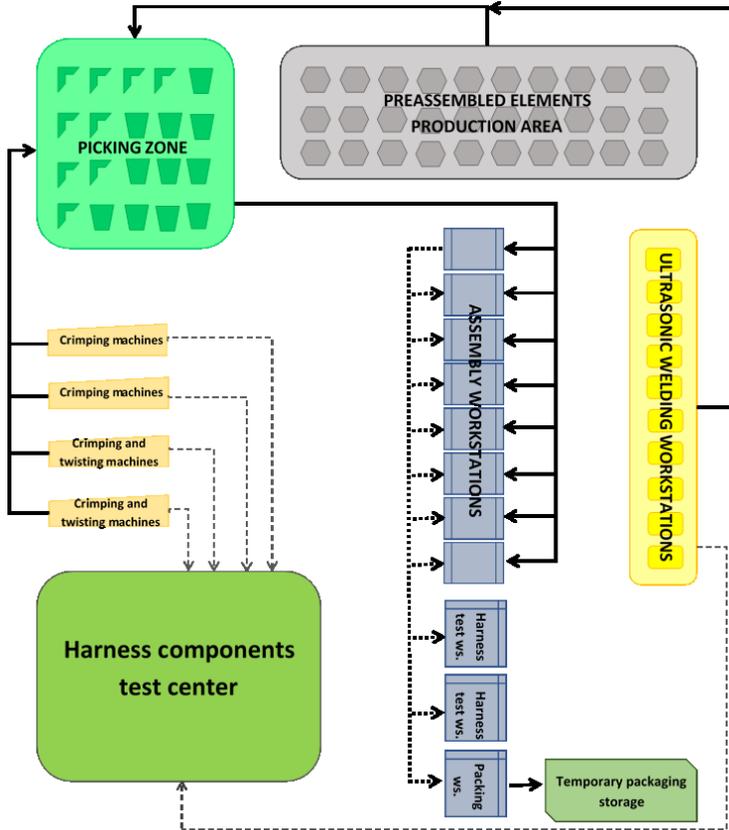


Fig. 4. Logistics flow of the dynamic assembly line

If an error is identified, on the label printed by the system at the end of the test it will be specified that a retouch must be made. Retouching a harness can be difficult depending on the area where the defect is located. For example, to replace a single wire, the protection of the harness and other fixation elements on the entire impacted area must be removed. Retouches are made with tools specially created for this purpose, with the help of which the defect is repaired without affecting the quality of the other components. After retouching, the wiring test process for all functions is resumed.

After the tests show that all functions can be performed by the wiring, a label confirming this fact is printed and applied to the wiring. [1]

Packaging wiring conditioning is also a manual process. The way in which the conditioning is done, the type of boxes used for transport, as well as the number of wiring stored in a box is established by the specifications together with the customer (car manufacturer).

The diagram from figure 9 highlights the logistics flow of the dynamic assembly line, providing an overview of how manual and automatic processes combine in the production of wiring.

4.4 Case study regarding harness assembly flow optimization

The case study aims to identify the main factor that affects the productivity of dynamic assembly line in wiring harness production. To this end, the following theoretical structure of the assembly line was defined in Witness Horizon Software:

- 13 workstations: 10 assembly workstations, 2 test workstations and one packaging workstation,
- 9 buffers: 5 buffers used for storing components, one buffer to deposit the harness before testing, one buffer for each test workstation to deposit the harnesses that do not pass the tests, one buffer before the packaging workstation to deposit the harness before packaging,
- a conveyor belt is installed below the assembly board to ensure the transport of harness branches from one workstation to another,
- the assembly line is serviced by 19 operators.

A single shift of 8 hours a day, 5 days per week, meaning 2400 minutes was simulated, as shown in the following figure:



Fig. 5. Dynamic assembly line simulation

Following the simulation, we notice that after workstation 4, the idle time for each workstation increases progressively, reaching a percentage of 97.56% at the last workstation.

Machine Statistics Report by On Shift Time

Name	% Idle	% Busy	% Filling	% Emptying	% Blocked	% Cycle Wait	% Setup	% Setup Wait	% Broken D	% Repair Wait	No. Of Oper
PL001	32.52	23.44	0.00	0.00	0.00	44.04	0.00	0.00	0.00	0.00	16
PL002	35.60	58.59	0.00	0.00	0.00	5.81	0.00	0.00	0.00	0.00	12
PL003	28.96	39.06	0.00	0.00	0.00	31.98	0.00	0.00	0.00	0.00	10
PL004	37.74	38.09	0.00	0.00	0.00	24.17	0.00	0.00	0.00	0.00	8
PL005	46.04	37.60	0.00	0.00	0.00	16.36	0.00	0.00	0.00	0.00	6
PL006	58.25	21.97	0.00	0.00	0.00	19.78	0.00	0.00	0.00	0.00	5
PL007	66.33	13.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4
PL008	94.14	5.86	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3
PL009	94.14	5.86	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3
PL010	95.12	4.88	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1
VerificareDim	95.12	4.88	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1
ControlloElettrico	95.12	4.88	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1
Ambalare	97.56	2.44	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1

Fig. 6. Shift simulation statistical analysis

This fact affects the productivity, causing a blockage in the production flow, as shown in the figure below:

Part Statistics Report by On Shift Time									
Name	No. Entered	No. Shipped	No. Scrappe	No. Assemb	No. Rejecte	W.I.P.	Avg W.I.P.	Avg Time	Sigma Ratin
Deriva001	16	0	0	12	0	4	3.28	41.97	6.00
Deriva002	12	0	0	10	0	2	1.50	25.66	6.00
Deriva003	10	0	0	8	0	2	1.09	22.35	6.00
Deriva004	8	0	0	6	0	2	1.00	25.56	6.00
Deriva005	6	0	0	5	0	1	0.71	24.25	6.00
Deriva006	5	0	0	4	0	1	0.36	14.60	6.00
Deriva007	4	0	0	3	0	1	0.25	12.75	6.00
Deriva008	3	0	0	3	0	0	0.21	14.00	6.00
Deriva009	3	0	0	1	0	2	0.22	15.00	6.00
Cablaj	1	1	0	0	0	0	0.12	25.00	6.00
Fire	1828	0	0	1083	221	745	609.14	68.25	6.00
Conectori	1831	0	0	315	217	1516	879.88	98.42	6.00
Banda	1815	0	0	81	233	1734	979.96	110.58	6.00

Fig. 7. Part statistic: report by shift time

In order to optimize the assembly flow, three hypotheses were considered:

- the first hypothesis was that reducing the working time by eliminating the idle time for all the workstation, would unlock the production. After a new simulation with the modified working time, the data shows this variant does not solve the blockage.
- the second hypothesis was that reducing by half the “Inter Arrival Time” (line supply time) would help reduce the idle time of the workstations. After simulating the assembly flow for one shift, no improvement was found.
- the third hypothesis consisted in redistributing the operations assigned to each workstation and re-evaluating the workload of the assembly line. This time the blockage was eliminated, the idle time was reduced, leading to the increase of the assembly line productivity. The results obtain after the simulation made with this hypothesis, show that redistributing the operations and downsizing with an operator (OP 13), led to an optimized production flow.

Machine Statistics Report by On Shift Time											
Name	% Idle	% Busy	% Filling	% Emptying	% Blocked	% Cycle Wai	% Setup	% Setup Wai	% Broken	% Repair Wa	No. Of Oper
PL001	45.23	54.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	119
PL002	50.42	49.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	119
PL003	50.73	49.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	118
PL004	50.83	49.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	118
PL005	56.10	43.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	117
PL006	61.00	39.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	117
PL007	66.10	33.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	116
PL008	75.83	24.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	116
PL009	75.83	24.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	116
PL010	85.56	14.44	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	115
VerificareDim	85.63	14.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	115
ControlElectri	86.00	14.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	112
Ambalare	86.00	14.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	112

Fig. 8. Shift simulation statistical analysis after optimization

Comparing the results obtained after optimization with those obtained before optimization, we can see that after optimization the fluidity of the assembly line increased significantly, and the waiting time between production cycles was eliminated.

Part Statistics Report by On Shift Time									
Name	No. Entered	No. Shipped	No. Scrappe	No. Assemb	No. Rejecte	W.I.P.	Avg W.I.P.	Avg Time	Sigma Ratin
Deriva001	119	0	0	119	0	0	0.55	11.00	6.00
Deriva002	119	0	0	118	0	1	0.54	10.94	6.00
Deriva003	118	0	0	118	0	0	0.54	11.00	6.00
Deriva004	118	0	0	117	0	1	0.49	9.93	6.00
Deriva005	117	0	0	117	0	0	0.44	9.00	6.00
Deriva006	117	0	0	116	0	1	0.39	7.95	6.00
Deriva007	116	0	0	116	0	0	0.29	6.00	6.00
Deriva008	116	0	0	116	0	0	0.29	6.00	6.00
Deriva009	116	0	0	115	0	1	0.19	3.99	6.00
Cablaj	115	112	0	0	0	3	1.70	35.51	6.00
Fire	24001	0	0	14127	0	9874	5076.25	507.60	6.00
Conectori	24001	0	0	4360	0	19641	9861.96	986.15	6.00
Banda	8001	0	0	1863	0	6138	3096.12	928.72	6.00

Fig. 9. Part statistic after optimization: report by shift time

The case study shows that for wiring harness assembly, because of the low degree of automation, the main factor that influence productivity is the distribution of operations to the workstations. High load workstations should be served by experienced operators (with high dexterity) and should be placed strategically across the line to ensure the fluidity of the assembly flow and reduce waiting time.

5 Future trends in automation of wiring harness assembly flow in the automotive industry

Although progress has been made in developing fully automated machines that can increase the degree of automation of harness production, there are still many constraints that need to be considered. The increased diversity of the options available on the vehicles, as well as the modifications that occur during the development phase of the vehicle, lead to high variety of variants that makes achieving full automation of wire harness production particularly challenging.

Over the past years important steps in finding automation solution for wiring harness production have been made. A new generation of insertion machines has already been developed to meet the challenge of component miniaturization, but their integration in the production flow depends on the degree of flexibility and the impact of the investment on the production costs.

In order to highlight the latest trends in harness assembly flow automation, two examples of automated machines will be used.

The first example is a fully automated machine (Zeta 640/650) that can perform the following operations: cut, strip, insert seal, crimp and double crimp wire of different sections and colors at the same time, reducing the production time up to 50%. It is also able to make a bundle of wires with different section and color. [4] The development of this type of machines shows an interest for finding and integrating automated equipment into the picking zone.

The second example is a fully automated machine (Omega 745/755) that does all the operations necessary to obtain a wires/connector subassembly, that can reduce the time and complexity of the operations executed on the final assembly line. According to the technical data available, it can perform the following operations: cutting, stripping, seal insertion and crimping up to 36 different wires at the same time (without a module changing needed), inserting the wires into the housing and closing the secondary lock of the connector housing. The insertion process is monitored by a high-precision force sensor,

ensuring the correct latching of the terminal parts in the housing even for the insertion of small components, providing in this way a solution to the component miniaturization problem.[4]

These are only two examples of automated solution for improving harness production technology, there are many other still in developing phase that will surely add value to the production process in the future. However, the implementation of the newly developed technical solutions will be made considering cost issues and the effect that it will have on the competitiveness of the harness manufacturer.

6 Conclusions

There is yet more research to be done in wiring harness automation. Despite the progress made in this field, there are still manual operation needed for which it does not exist an automated technical solution. There are many constraints to be taken into consideration before deciding to invest in increasing the automation degree, and the decision must be made having a complete overview of the production process and investment cost correlated with maintaining short-term competitiveness on the market.

Therefore the full automation will not happen overnight and will not be achieved by all wiring harness manufacturers, but the ones that will manage to increase their automation degree will have a leverage over the others, being able to produce at higher quality level and at better cost.

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