SIMILARITIES AND DIFFERENCES IN THE PROCESS OF AUTOMATING THE ASSEMBLY OF RIGID BODIES AND ELASTIC ELEMENTS OF PNEUMATIC TIRES

Podobieństwa i różnice w procesie automatyzacji montażu brył sztywnych oraz elementów plastycznych opon pneumatycznych

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Abstract: The paper presents the classification of tyre elements intended for automatic and robotic assembly into rigid bodies (material points within the geometric part of the element cannot move against each other) and plastic elements (subject to irreversible deformation under the influence of external forces, temperature, gravity, which act on the unvulcanised tyre elements). The assembly process has been divided into 7 closed-loop areas of the automation and robotisation process of industry 4.0 factories in order to demonstrate the similarities and differences that affect the degree of automation and robotisation of assembly. Characteristic features of rigid bodies and plastic elements are also described. Plastic elements of the tyre prior to vulcanization are characterized by internal friction due to shifting of its individual layers in relation to one another. The placement of layers has a major impact on the selection of technology, machines and instrumentation necessary for the automation and robotisation of production processes in modern factories and logistics centres. The author presents several examples of physical and geometric features facilitating the automation of rigid bodies and plastic elements assembly, as well as their positioning on the machine in the process of multi-layer tyre production. The multi-layer nature of pneumatic tyres determines the process of designing automatic and robotic assembly stations, which is only possible after the completion of the tyre design.
Keywords: assembly, rigid body, plastic element, tyre, automation

Streszczenie: W pracy przedstawiono klasyfikację elementów przeznaczonych do montażu automatycznego i zrobotyzowanego na bryły sztywne i elementy plastyczne. Proces montażu podzielono na *7 obszarów stanowiących pętlę zamkniętą procesu automatyzacji i robotyzacji fabryk przemysłu 4.0. Opisano cechy charakterystyczne brył* sztywnych i elementów plastycznych oraz *lepkich*, które mają główny wpływ na dobór technologii, maszyn i oprzyrządowania niezbędnego do automatyzacji oraz robotyzacji procesów produkcyjnych w nowoczesnych fabrykach i centrach logistycznych. Przedstawiono kilka przykładów cech fizycznych i geometrycznych ułatwiających automatyzację brył sztywnych i zasady pozycjonowania elementów plastycznych oraz lepkich. Następnie, opisano zagadnienia wielowarstwowość opon pneumatycznych i uwarunkowania wpływające na proces projektowania automatycznych i zrobotyzowanych stanowisk montażu, który poparto przykładami przedstawionymi na rysunkach. Kolejny etap pracy przedstawia właściwości fizyczne elementów opon, które ułatwiają automatyzację i robotyzację procesów technologicznych montażu. W podsumowaniu zdefiniowano proces technologiczny montażu elementów opon.
Słowa kluczowe: montaż, bryła sztywna, element plastyczny, opona, automatyzacja

Introduction

The automation of production and logistics processes has been developing over the past 20 years, as evidenced in the report *Opportunities and challenges for the Polish Industry 4.0* [1]. Based on the information published on the website of the Ministry of Development, Labour and Technology in the article *Tax relief for robotisation - new support measures from 1 January 2021* [2] it can be assumed that automation and robotization will continue to develop dynamically.

Automatic assembly processes are optimised in terms of work organisation, logistics and technological equipment. Numerous researchers are dealing with assembly technology and automation, including, in particular: Jerzy Łunarski, Jan Żurek, Jerzy Honczarenko, Olaf Ciszak, and others, who in their works address issues such as innovative design technologies, as well as implementation and use of automated and robotic workstations. According to the author of the paper, the classification of literature on the subject of assembly technology and automation can be divided into 5 basic topics:

1. selection of the assembly sequence variant for machine parts and assemblies [3],
2. balancing assembly lines to shorten the assembly time, consideration of its various organisational variants, and subsequent selection of the optimal process depending on the established criteria [4, 5, 6, 7],
3. designing for manufacturability, ensuring the positioning of the assembled elements in the shortest possible time, while maintaining the required technological and structural parameters [8],

4. development of machines and tools used in assembly automation processes [9, 10, 11, 12]
5. mathematical description of assembly processes, technologies and automation [13].

Progress in the field of automation and robotisation is possible thanks to the development of machine vision technologies and contactless measurement sensors, as well as the use of physical and geometrical characteristics of elements that can be grasped and moved from place to place without their deformation.

Characteristic features of rigid bodies and plastic elements of tyres which have an impact on the automation and robotisation of production processes in Industry 4.0 factories and warehouses

In the automation of many industrial technological processes, the physical and geometric properties of rigid bodies are used [14, 15], which retain their physical properties when exposed to various forces during transport, positioning or assembly, and even if some deformations occur, they do not affect the quality of the final product. Progress in the field of assembly automation and robotisation was initiated in the automotive and home appliances industry due to the high volume of production. Currently, an increasing degree of automation is also observed in the food, pharmaceutical and logistics industries.

The author of this paper has divided the automation and robotisation process into 7 closed-loop areas of the technological process of industry 4.0 factories, which can be applied to the assembly of tyre elements:

1. **warehouse logistics I** (receipt of raw materials at the warehouse):
   a. identification of the needs of individual departments,
   b. automation of the order schedule,
   c. transport of raw materials to the production plant,
   d. designation of an area in the warehouse,
   e. unloading deliveries and receipt of raw materials and parts at the warehouse (e.g. via mobile robots, automated cranes and other specialised logistics equipment),
   f. segregation and storage (with the use of specialised logistics equipment),
   g. preparation of raw materials and parts for technological processes (rotation of raw materials in the warehouse in order to maintain the correct order of their release for production and to prevent the accumulation of outdated raw materials in the warehouse),
2. **process logistics I** (ensuring continuity of supplies for production workstations):
   a. identification of the needs of individual workstations,
   b. automation of the information flow from the workstations to the warehouse,
   c. automatic retrieval of the required items from the warehouse,
   d. delivery to workstations (e.g. via feeders, specialised tables and containers transported by mobile robots and other specialised logistics equipment),
   e. transport of parts and assemblies between workstations, where they are assembled into subassemblies and assemblies (e.g. with the use of specialised pallets, carriages, feeders),
3. **positioning of elements to be joined I** (making use of the specific shape and position of the centre of gravity of the manipulated element, e.g. for gravitational movement of elements stopped on buffers)
   a. unambiguous orientation of parts (workstations equipped with sensor systems),
   b. preparation of the part for gripping, movement and operation,
4. **technological process of assembly** (mutual alignment of parts and fixing their position by screwing, thermal clamping, soldering, welding, sealing, gluing and stitching for rigid bodies; in the case of plastic elements of tyres, adhesion is used for joining and minimum pressure is applied so as not to cause their permanent deformation):
   a. orientation in space and measurements before the technological operation,
   b. execution of the technological operation in accordance with the planned operational procedures,
   c. orientation in space and measurements to verify the quality of the joint,
   d. sending notification to the process control system about the completion of the process and its results
5. **positioning of joined elements II** (making use of the specific shape and centre of gravity of the manipulated element, alignment to the buffers or other orientation of the product in space)
   a. unambiguous orientation of the product to prepare it for removal from the assembly zone,
   b. gripping and moving the product to the designated place after completion of the technological operation,
   c. measurement of the geometry and weight of the product,
   d. sending information to the production process control system,
   e. assignment of an appropriate identification code,
   f. transfer and placement of the finished product in the designated area, pallet, etc.
6. **process logistics II** (transfer of subassemblies and assemblies between individual workstations; delivery of the assembled elements to the warehouse after completion of the assembly process, e.g. using feeders, conveyors, containers, robots and similar equipment)
   a. identification of the product,
   b. sending information to the process control system,
   c. determination of the subsequent storage location (for work in progress),

   d. transport of parts and assemblies between workstations to the clearly specified place,
   e. delivery of assembled products to a clearly specified place in the warehouse (e.g. with the use of feeders, specialised containers, carriages, mobile robots and similar equipment),
7. **warehouse logistics II** (issuing products) - receiving the finished product into the warehouse, storage, issuing the assembled product and repeating the cycle.
   a. identification of the recipients' needs,
   b. automation of the shipping schedule (taking into account the rotation of products in the warehouse),
   c. optimisation of transport to customers (optimal placement of the goods in a truck or freight car),
   d. searching for and identification of products in the warehouse,
   e. transfer of the finished product to the loading area of vehicles or railway cars,
   f. validation of conformity of the shipped goods with the order,
   g. loading (e.g. by means of mobile robots, automated cranes and other specialised logistics equipment).

This process is identical for the assembly of many popular devices and is shown graphically in Figure 1.

Warehouse logistics I and II (Fig. 2) and process logistics I and II (Fig. 3) are mentioned twice in the above-mentioned classification. These are, in principle, the same processes (the diagrams in Figures 1, 2 and 3 are universal for different industries) and are listed twice since the assembly technology uses different feeders, racks, pallets and tooling for the assembly components before and after assembly. After the completion of the assembly technological process, different dimensions, mass and functionalities are obtained (hence, a different type of tooling must be used than before). When designing an automated and robotic technological process, the designer cannot assume that auxiliary tooling will be used for the same components before and after assembly. The parameters of overall dimensions, individual dimensions, shape and mass characterising the technological assembly processes of tyre components can be defined as follows:

1. **overall dimensions** – the outline of the component with maximum external dimensions,
2. **dimension** – the physical distance between points that mark individual surfaces of a component or assembly,
3. **shape** – the measurable relationship between all surfaces of a component that can be described with dimensions and tolerances of straightness, flatness, circularity, cylindricity, line and surface profiles, which can be used to characterise a component or an assembly,
4. **mass** – the parameter defining inertia and gravitational interaction of components or assemblies of the assembled product.

Changes in the mass and shape of a component have an impact on the position of its centre of gravity and the value of the moment of inertia, which is decisive when designing drives and selecting parameters of the drive system. The tyre industry uses very heavy and large machinery that must ensure stability of the assembly process and high productivity. Tyre assembly in most

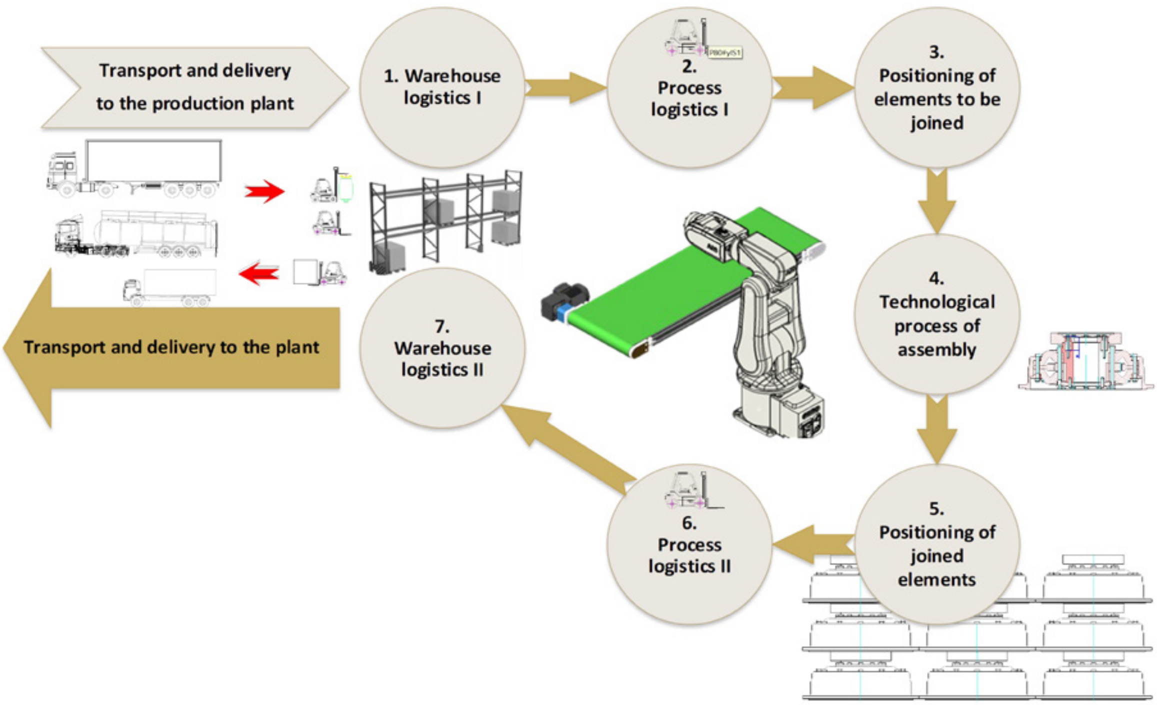

Fig. 1. Closed loop of the automation and robotisation process of Industry 4.0 factories [own elaboration]

plants is a serial production process. Disregarding the moment of inertia in calculations can lead to serious accidents in the workplace (as a result of changes in the weight and size of the product during the tyre assembly process due to the winding of successive tyre layers). For example, in the Bridgestone production plant in Poznań which manufactures passenger car tyres, there were as many as 36 accidents and 20 incidents at work in 2019 alone [16]. Fatal accidents in tyre factories are not uncommon, either (e.g. the accidents in Olsztyn in 2006 and 2011) [17, 18].

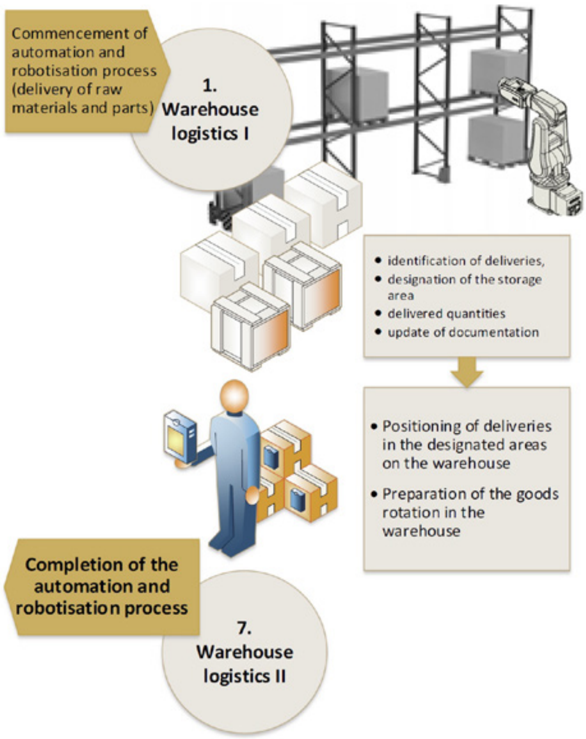

Fig. 2. Warehouse logistics I is the first stage of the automation and robotisation process of Industry 4.0 factories enabling the continuity of production [own elaboration] Fig. 4. View of the Appendix sheet for assembling the bus engine [2]

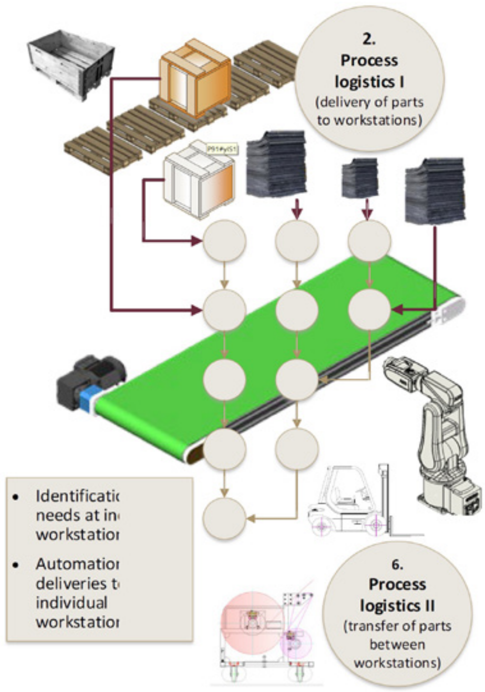

Fig. 3. Process logistics I and II are the stages of production in Industry 4.0 factories enabling automation and robotisation of processes between workstations [own elaboration]

According to the author of this paper, when it comes to the assembly technology, the maximisation of the use of the physical and geometric features of the joined components should be ensured. Works conducted in the industry in the period 1998-2020, including projects presented in the technology database of the Agencja Rozwoju Przemysłu S.A. [19, 20, 21, 22, 23, 24, 25, 26] and patented works [27, 28, 29, 30, 31, 32] allow to conclude that designing the technological processes of automatic tyre assembly can be facilitated by:

1. **defining the minimum stiffness** (no deformation of tyre components due to external and thermal stresses) - required for the selection of equipment for storage and positioning of tyre components (Fig. 4); if the tensile strength is exceeded during the assembly process the tyre component is damaged (Fig. 5),
2. **determining the mass of the components and the range of their inertia and unwinding speed, as well as the torsional torque and the clamping force** – required for the selection of operating parameters of the system elements necessary for the orientation and positioning of the components in space (Fig. 6),
3. i**dentification of dimensions and shapes** – specific dimensions are taken into account to select the required workspace and confirm the quality and correctness of the selected components (Fig. 7),
4. **using the moment of inertia and other physical relationships** – required for the positioning of rigid body type parts and setting unwinding parameters for plastic parts (Fig. 8 and 9
5. **concentration of raw materials and parts processing in pre-assembly processes**, as well as minimisation of the number of product components and simplification of their shapes (Fig. 10),
6. **using colours and codes for identification of components in the assembly process** (optical sensors and thermal imaging cameras for process supervision (Fig. 11).

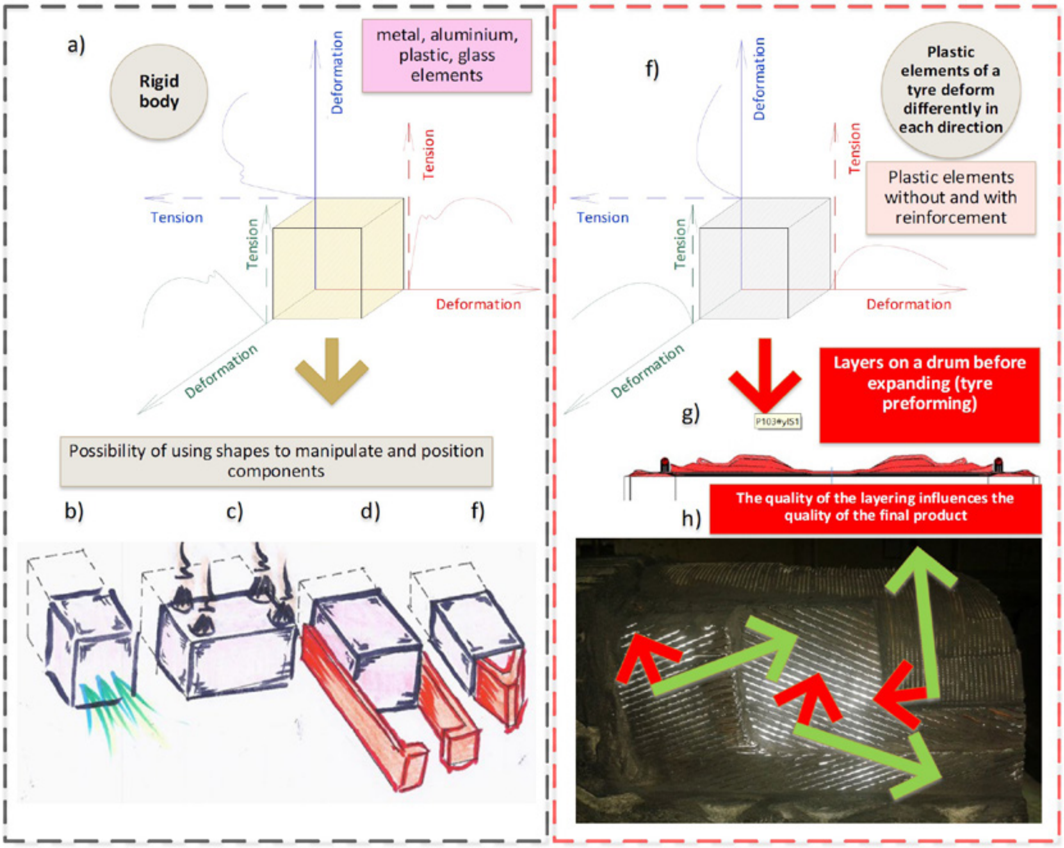

Fig. 4. Defining the minimum stiffness and dimensional stability of components to determine the parameters of grippers, bumpers and similar solutions in different configurations. 2.a) Minimum stiffness and dimensional stability to allow the use of grippers, bumpers, regular and specialised containers. The manipulated component may have different strengths in different planes and directions of forces. The weakest contact point and pressure exerted by the handling system are assumed. The force exerted must not exceed the tensile or compressive strength. 2.b) Displacement of parts with compressed air blast (e.g. blowing off incorrectly manufactured parts). 2.c) Transport by a vacuum system with vacuum suction nozzles and ejector pumps (e.g. gripping of parts which are very difficult to transport such as car windows). 2.d) Handling and free manipulation of any component by means of grippers exerting friction between the gripper surface and the handled component (e.g. pneumatic or hydraulic grippers, etc.) 2e) Pushers, locking devices of various shapes and drives (electric, pneumatic, hydraulic, spring) for sliding, positioning and other functions depending on the industrial application, 2f) Tyre elements are subject to substantial deformation at low stresses of 0.5 - 3.5 MPa. 2g) Layers on the drum of a tyre manufacturing machine. 2h) Example of tyre layering and different tensile strength of individual layers in each direction [own elaboration].

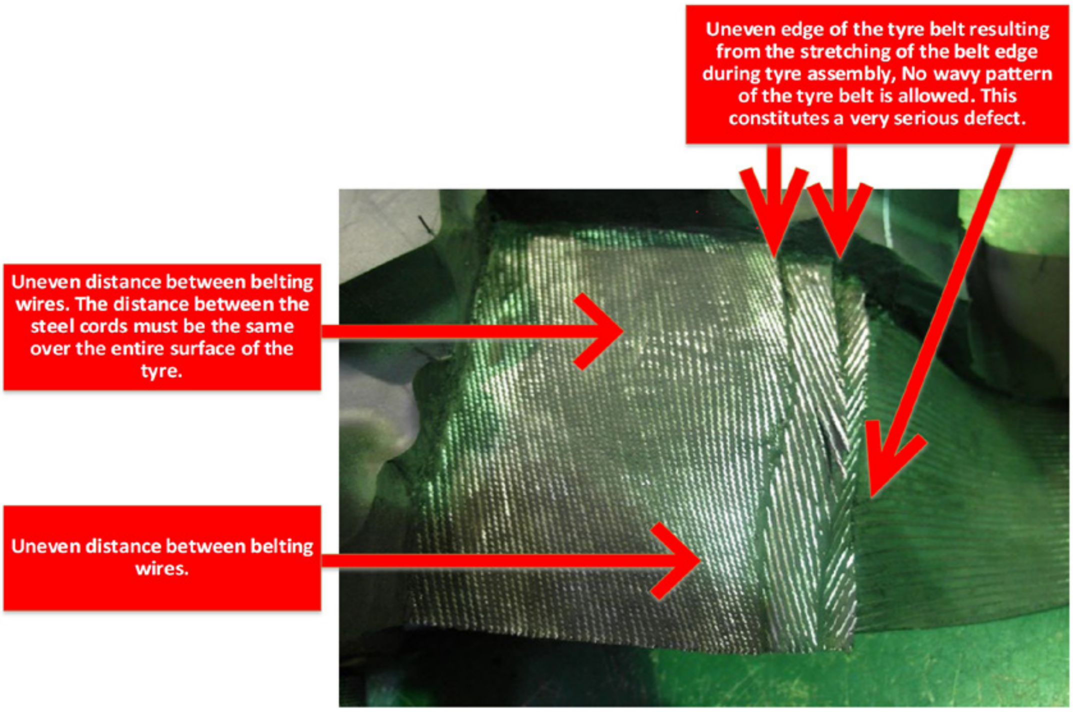

Fig. 5. Example of exceeding the tensile strength limit during the assembly of tyre belt elements [own elaboration]

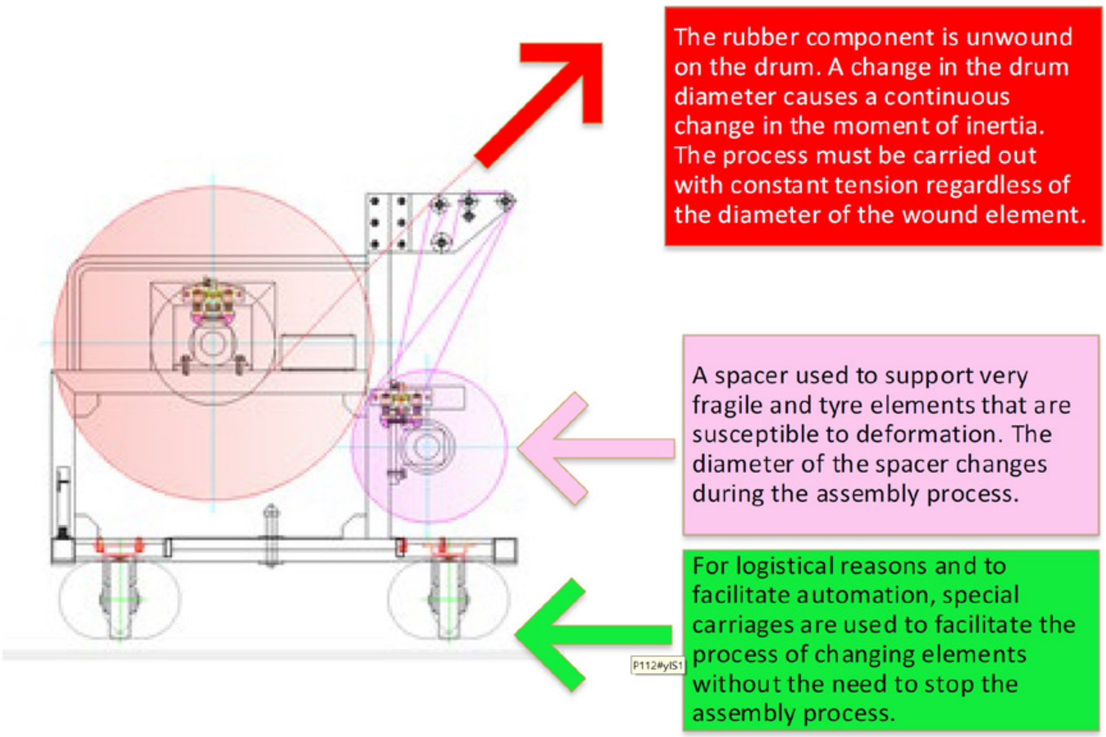

Fig. 6. During the process of tyre elements assembly, the mass of the wound elements and their inertia, as well as the unwinding speed are constantly changing. For this reason, the drive must be equipped with the measurement systems of the unwinding force, the diameter of the wound tyre element and the the diameter of the spacer [own elaboration].

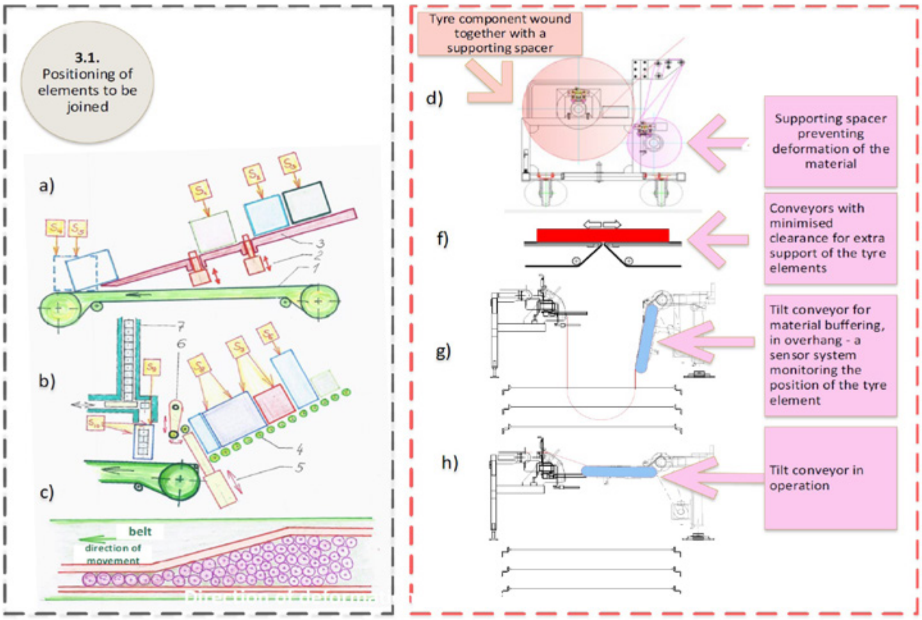

Fig. 7. Gravitational and friction forces facilitating transport and handling of components, as well as their orientation in space. 3.a) Example of the use of a belt conveyor 1, which the elements waiting on the gravity conveyor 3 are fed on after inserting a pin 2, which can be driven electrically, pneumatically or by a hydraulic actuator. The sensor system S1÷S5 can recognise colours, positions, bar codes and letters. 3.b) Elements of various shapes, sizes and weights may be placed on the gravitational conveyor 4 to shield the buffers 5 and 6. Shifting the position of the buffers moves the element onto the conveyor which transports it in order to insert an appropriate number of parts stored in the feeder 7 cooperating with the pusher. The pusher is activated after an appropriate positioning of the elements on the conveyor by means of the sensors S9÷S10 (e.g. optical sensors detecting the edges of the elements and counting the number of inserted elements from the feeder 7). 3.c) The principle of buffering and positioning multiple rotating elements, the movement of the conveyor and the possibility of exerting friction and rotation causes the elements to line up individually. 3.d) A carriage with wound tyre elements and a spacer to prevent deformation and sticking of the wound coils of material. 3.e) Transfer of elements by means of conveyors positioned with a minimum gap so as to prevent damage of the transported element. 3.g) Buffering tyre elements by means of a tilt conveyor and a system of sensors measuring the maximum overhang of the material to prevent it from damage due to gravitational forces (the greater the mass of the material, the greater its weight and the risk of stretching along the length, causing narrowing in width). 3.h) After the completion of buffering, the conveyor is lifted so that the material is not exposed to deformation [own elaboration]

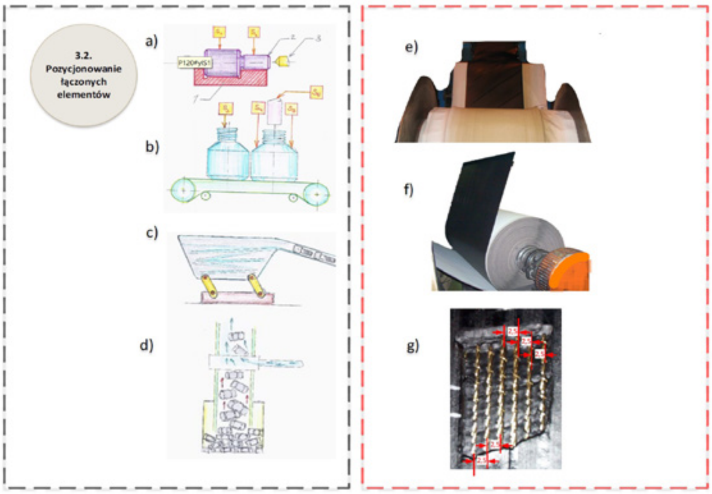

Fig. 8. Identification of shapes. 8.a) Elements 2 can be placed on the feeder 1, and their position is verified by the sensor system S1÷S2; an element positioned in such a way can be gripped, for instance by centre holes. 8.b) Bottles may be placed on the conveyor, the quality of which is verified by sensor S3 immediately prior to their filling (e.g. by an optical sensor with stored pattern of correct thread quality), the correct position for pouring is measured by sensors S4 and S5, then the bottle is filled and the amount of dispensed liquid is controlled by sensor S6. 8.c) Possibility of using vibrating systems. 8.d) Vacuum or pneumatic conveying and feeding systems. 8.e) Systems for supporting tyre elements on spacers (fabric or plastic spacer with anti-adhesive properties and sufficient rigidity to support the plastic elements). 8.f) and 8.g) Separation of the spacer from a plastic element reinforced in one direction with a steel cord, where individual steel elements are aligned at the same intervals across its width [own elaboration]

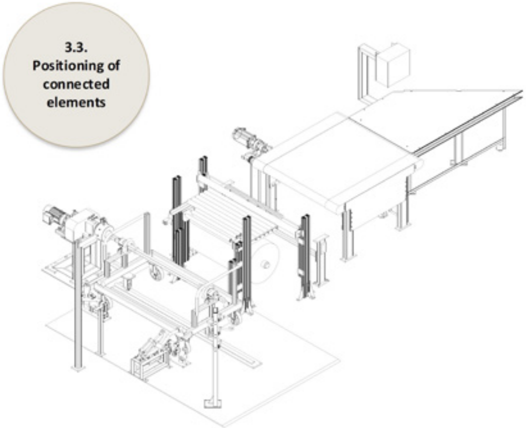

Fig. 9. An example of a winder for plastic elements of the tyre, in which the above-mentioned components are used [own elaboration].

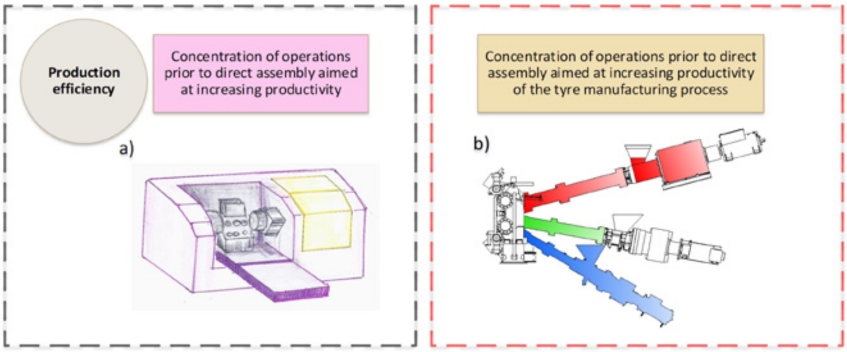

Fig. 10. Concentration of raw materials processing in pre-assembly processes, as well as minimisation of the number of product components and simplification of their shapes. Fig. 10.a Multi-axis machine tools, rotary tables, possibility of turning, milling and drilling, interchangeable machine tables, wide doors to the machine interior enabling the use of an overhead crane or a robot to insert and remove elements, multi-tool magazines, as well as direct measurement of processed elements and tools used in the process. Fig. 10.b In the tyre production process, concentration mainly consists in making as many joined elements as possible on the extruder systems so that joining of the elements takes place directly in the extruder head [own elaboration]

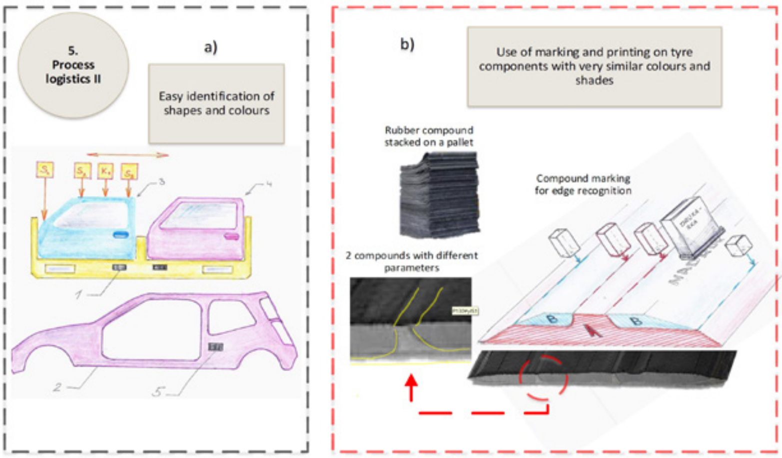

Fig. 11. The use of element colours and bar codes to automate the process of searching for goods in a warehouse. Fig. 11.a The camera K1 allows to find the right colour of an element (e.g. a door of the colour 3 or 4) positioned on the pallet 1. After finding the right pallet based on the bar code (comparison with the code on the body 5), the element is grasped by the manipulator positioned on the basis of measurements taken by sensors S1÷S3 and the camera K1. Fig. 11.b The use of the colours of the elements, sensors and thermal imaging cameras to supervise the processes. The compounds are very similar in colour, dimensions and mass. In order to identify the products on the tyre manufacturing machine, colour printers can be used at the component manufacturing stage to mark the boundary lines of the individual material layers and print the component codes. The use of optical sensors on the machine allows for error-free identification of components and their centring. The letters A and B mark compounds with different parameters. [own elaboration]

The assembly technology used for rigid body type components cannot be directly applied for plastic elements, including unvulcanised rubber compounds, as well as textile and steel components joined during the tyre assembly process. Unvulcanised tyre components are very susceptible to deformation. Only after the **vulcanisation** process, the product takes on its final shape and the required strength. For the purpose of this paper, vulcanisation can be defined as *a process of high-pressure heat treatment of the assembled tyre components, after which the product is cooled and dimensional stability of the product is ensured to achieve the required fatigue limit*.

The main strength parameter of tyre components during the assembly process is their tensile strength, which ranges between 0.5 and 3.5 MPa. These values are very low compared to steel, cardboard, glass and plastic components, and makes plastic components very susceptible to damage. For example, general purpose carbon steel of ordinary quality in accordance with EN 10027-2, marked as 1.0035 (also known in the industry as St0S or S185) reaches a tensile strength of 314 [MPa], alloy steel for quenching and tempering marked as 45HNMF reaches 1470 [MPa], while the value for tool steel 65S2WA can be as high as 1860 MPa. Modern cardboard packaging is much less plastic, with very rigid structure in one or several selected directions (e.g. Cardboard boxes for storing raw materials and vegetables, packages arranged in several layers on one pallet). The parameters of packaging are defined by the index of corrugated board resistance to edge crushing, marked by the abbreviation ECT [33]. Depending on the packaging design, it ranges from 2 to 10 kN/m. The strength of cardboard packaging increases if the products placed inside the box can be used to reinforce it (e.g. cans or containers filled with liquid). Another parameter, less commonly used in the packaging industry, is the flat crush resistance of the packaging wall (FCT), expressed in N. In the case of plastic elements used for the manufacturing of tyres, such a parameter is practically non-existent in industrial practice. The processes of packaging, handling of cardboard boxes, their positioning on transport pallets and stacking into layers are increasingly widely automated. Handling of cardboard boxes in the process of automation and robotisation is subject to the principles of rigid bodies handling, provided appropriate humidity parameters are ensured, as excessive humidity can lead to the deterioration of ECT and FCT parameters. For this reason, even the automation of the assembly and transport of cardboard boxes is much easier to achieve as compared to tyre components.

In the case of products made of rubber compounds, such as tyres, the rigid body handling principles can be applied only after the completion of the vulcanisation process and ensuring the dimensional stability of tyres. Tyres take on their final shapes after they are removed from the mould and cooled to ambient temperature. After the completion of the entire production process, the components made of rubber compounds reach a tensile strength of 5 up to 25 MPa. From this point, tyres can be positioned, gripped and stacked like regular rigid bodies.

An important parameter of super plastic components is their hardness. For the purpose of this paper, plastic elements have been divided into *6 hardness categories that determine the way of automation and robotisation of the technological process of tyre assembly*:

1. very soft from 5 to 50 on the shore Shore 00 hardness scale :
   a. difficult to automate,
   b. requires the use of spacers
2. soft from 10 to 30 on the Shore A scale,
   a. difficult to automate,
   b. requires the use of spacers
3. medium hard from 40 to 60 on the Shore A scale,
   a. possible to automate,
   b. requires the use of spacers
4. slightly hard from 60 to 80 on the Shore A scale,
   a. possible to automate on a rigid body basis,
   b. does not require the use of spacers
5. hard from 80 to 100 on the Shore A scale,
   a. easy to automate - the component behaves like a rigid body.
   b. does not require the use of spacers
6. very hard from 60 to 100 on the Shore D scale,
   a. very easy to automate - the component behaves like a rigid body.
   b. does not require the use of spacers

Plastic element (rubber compound before vulcanisation) becomes easily deformed and in contact with any fixes, immovable part, it sticks to it. Removal of compacted and jammed rubber compound from the machine's workspace and spaces between the machine parts is complicated and poses a risk of a serious accident. Rubber compound processing is a very dangerous process for operators, and, for this reason, modern Industry 4.0 factories use sensors and safety systems to protect staff from accidents. These measures will be described in detail by the author in another publication.

An additional difficulty in the process of tyre assembly is the fact that the hardness of the compound depends on temperature, as evidenced by the research conducted by H. J. Q. K. Joyce and M. C. Boyce, who describe a simulation of hardness tests and elastomer behaviour between tension and deformation [34]. According to the researchers, the predictive ability of the simulation (predicting statistical characteristics of random phenomena) is verified by comparing the calculated Shore A and D values with the conversion table presented in ASTM D2240. The simulation results are then used to determine the relationship between the neo-Hookean model [35] (based on statistical thermodynamics of cross-linked polymer chains, useful for plastics and rubber-like substances) and the Shore A and D hardness values. Transport-related issues, including heat transfer, dimensional analysis of polymer flow, convective momentum, energy and mass transfer, as well as transport in dual-phase systems have been described by R. B. Byron Bird, W. E. Stewart and E. N. Lightfoot [36]. In turn, the issues of polymer fluid dynamics are presented in a scientific publication by R. B. Bird, R. C. Armstrong and O. Hassager *Dynamics of Polymeric Liquids* [37]. Hardness is a frequently used parameter in the tyre industry and in order to standardise nomenclature nomenclature and testing methods, the industry uses standards. The standard described in ASTM D1415 – 18 [38] concerns hardness measurements in the regular elasticity range, and does not apply to materials with high stress relaxation factors or strain hysteresis - in which case it is recommended to use the hardness testing method described in ASTM D2240 – 15e1 [39] and ASTM D1415 – 06 [40]. Measurement readings for rubber compounds may differ when performing the test due to irregular specimen shapes. Elastomers undergo locally large deformations during hardness testing and simulations are performed to limit elastomer stretching during measurement. The standard practice for testing rubber compounds in the automotive industry is based on ASTM D1349 – 14 [41] and ASTM D4483 – 20 [42]. ASTM D1646 – 19a [43] defines other standard test methods for rubber compounds including - measurements of viscosity, stress relief and pre-vulcanisation characteristics - determined with a Mooney viscometer.

The implementation of the above-mentioned principles and procedures for positioning pre-vulcanised rubber components precludes the application of solutions used for positioning components classified as rigid bodies. This is due to the fact that, depending on the temperature and storage time of the raw material, the parameters and properties of rubber compounds change, which hinders conventional automation and robotisation of the assembly process of plastic tyre components. Table 1 presented below lists the properties of the assembled elements which have an impact on the selection of technological settings in operations and procedures of the automated and robotised production process, including the assembly of plastic tyre components.

Table 1. Plasticity and hardness of components influencing the process of assembly automation and robotisation (selection of equipment and technological process settings)

Possibility of automation and robotisation				
Unvulcanised compound	**Vulcanised compound**	**Corrugated cardboard packaging**	**Plastics**	**Steel**
Tensile strength 0,5 ÷ 3,5 [MPa]	Tensile strength 5 ÷ 25 [MPa]	Tensile strength 12 ÷ 19 [MPa]	Tensile strength 33 ÷ 650 [MPa]	Tensile strength 314 ÷ 1860 [MPa]
5 ÷ 50 Shore 00 scale	30 ÷ 80 Shore A scale	2 ÷ 10 ETC [kN/m]	50 ÷ 400 ball indentation hardness [MPa]	180 ÷ 460 HB hardness
Elements very sensitive to shape changes	Elements not sensitive to shape changes	Elements not sensitive to shape changes in selected directions	Elements not sensitive to shape changes	Elements not sensitive to shape changes
Implementation of automation and robotisation process very difficult	Implementation of automation and robotisation process easy	Implementation of automation and robotisation process easy	Implementation of automation and robotisation process easy	Implementation of automation and robotisation process very easy compared to tyre components
For the purposes of automation and robotisation of processes, spacers are used to prevent damage to the joined elements; all drives must gently accelerate and decelerate; tyre components are stored on carriages or special pallets in stable temperature and humidity.	After the vulcanisation process, products can be positioned using bumpers and automated conveyor systems, and moved using robots.	Possibility of using conveyors, bumpers, robots - positioning and gripping of elements by their surfaces and edges reinforcing the cardboard.	Possibility of using conveyors, bumpers, robots - positioning and gripping of elements by reinforced edges of the element structure.	Possibility of using conveyors, bumpers, robots.

Multi-layer pneumatic tyres and conditions determining the process of automation and robotisation of tyre assembly

Tyres are made up of numerous components, as evidenced by patents of such companies as: Michelin [44], Bridgestone [45], Goodyear [46], Continental [47], Yokohama [48]. In industrial practice, vulcanised rubber compound which is not adhesive, has higher tensile strength in MPa, lower elongation in % and hardness described in the Shore scale in accordance to the PN-ISO 868 standard, is used [49].

Based on years of observational studies and the author's design work mentioned at the beginning of the article - tyres can be defined as - *a pressure vessel made of multilayer composites with different strength parameters in different points of its cross-section, which are characterised by fatigue resistance and good vibration damping*.

Tyres should not be treated as a monolithic structure, as its multilayer structure provides resistance to the constantly exerted variable external and internal forces that cause material fatigue. Contemporary tyres must be resistant to material cracking caused by cyclically varying fatigue stress and vibrations of variable amplitude, caused by such overlapping factors as the roughness of asphalt surfaces, wind force, lateral wind gusts, the condition of the vehicle and its load. The more technologically advanced the tyre construction, the more complex the structure of its cross-section. Monolithic tyres are more likely to quickly get damaged, which is why tyres used, for example, in fork lift trucks, have varying strength properties at different points of their cross-section. The multi-layer structure of the tyre ensures a smooth transmission of tensile and compressive stresses. Textile and steel elements serve as reinforcement for the rubber compounds. Cord strands are stronger than single wires. This is due to the favourable ratio of cross-section to the number of fibres or wires in the cord. In addition, such a solution provides the necessary flexibility, which single threads or wires cannot ensure. The multilayer solutions used in contemporary tyres guarantee high quality and safety for users. In order to achieve consistent quality of tyres, great precision during the positioning of their components is required. Precise positioning of elements and durable bonding of individual layers after the vulcanisation process are presented in patent descriptions [50, 51, 52, 53]. An example of tyre structure is shown in Fig. 12 published in patent application P.411809. "*Under the base (2) of the tread (1) there are at least four layers (3) of rubberised steel cord; between the mentioned layers (3) and the bottom sealing layer (4) of the tyre there is an intermediate reinforcement layer (5). Both outer ends of at least three layers (3) of the rubberised steel cord are surrounded by protective wraps (6) and are equipped with positioning rubber wedges (7). In addition, in the tyre shoulder, between the reinforcing intermediate layer (5) and the carcass layer (8), there is a positioning rubber insert (9) in the shape of an elongated C letter. The tyre bead contains a three-part wing (10) surrounded along with the wire (11), by two rubberised steel cords (12) and a rubberised textile cord (13). Both ends of the rubberised steel cords of the bead are protected by wraps (6), while the outer parts of the bead are equipped with reinforcing wedges (14) located between the side wall (15) of the tyre and the protective wraps (6) of the steel cords (12) of the bead.*" [53].

Depending on their dimensions and use, tyres have different structures and performance characteristics (maximum speed, load capacity, nominal pressure, rolling radius, tread height and shape, circumference, rolling resistance, noise and braking distance on wet surfaces). More information on tyre structures can be found in patent publications of tyre manufacturers which have been developed in an empirical way over years. These patents constitute very valuable and legally protected knowledge. The difficulty in the access to scientific publications hampers the development of companies with more limited

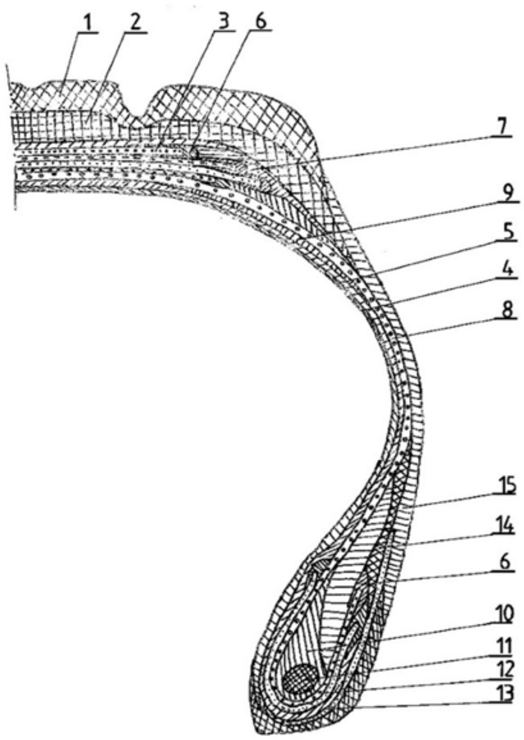

Fig. 12. Example of tyre structure described in the text [53].

intellectual potential, which experience difficulties in the acquisition of knowledge and implementation of new structural and technological solutions that would not infringe the intellectual property rights of their competitors.

The structure, number of layers and equipment determines the design of the assembly process. Tyre manufacturing machines have multiple stations for unwinding materials, positioning and cutting parts immediately prior to their assembly on the drum, which ensures the required accuracy of the process. The length of such machines ranges from a few to a dozen or so metres, and is due to the need for gentle centring of and protection of tyre elements.

Assembly of plastic components of tyres

Measures that facilitate automation and robotisation of technological processes of tyre assembly include:

1. defining the minimum stiffness and dimensional stability of the components in order to determine the parameters required to avoid deformation of the tyre components, e.g. by eliminating all factors that may cause deformation of the thin tyre components – as shown in Fig. 13,
2. concentration of raw material processing operations in pre-assembly processes, as well as using such parameters as mass, shape, temperature and pressure to control the processes of joining of the individual components, e.g. example in Fig. 14,
3. making use of the position of material support rollers to correct the position of the rubberised cords, as well as magnetic field to position the rubberised metal components of the tyre – Fig. 15,
4. making use of colours of the components, sensors and thermal imaging cameras to supervise processes and automate component identification – Fig. 11.

The tyre assembly process can be presented in the form of a diagram shown in Fig. 16, which summarises the main technological operations involved. The issue of tyre assembly process optimisation is extremely important from the point of view of road users. It is a very complicated process, since the individual layers at the stage of their assembly are very susceptible to permanent deformation, which entails a deterioration in the final product quality, as shown in Fig. 5.

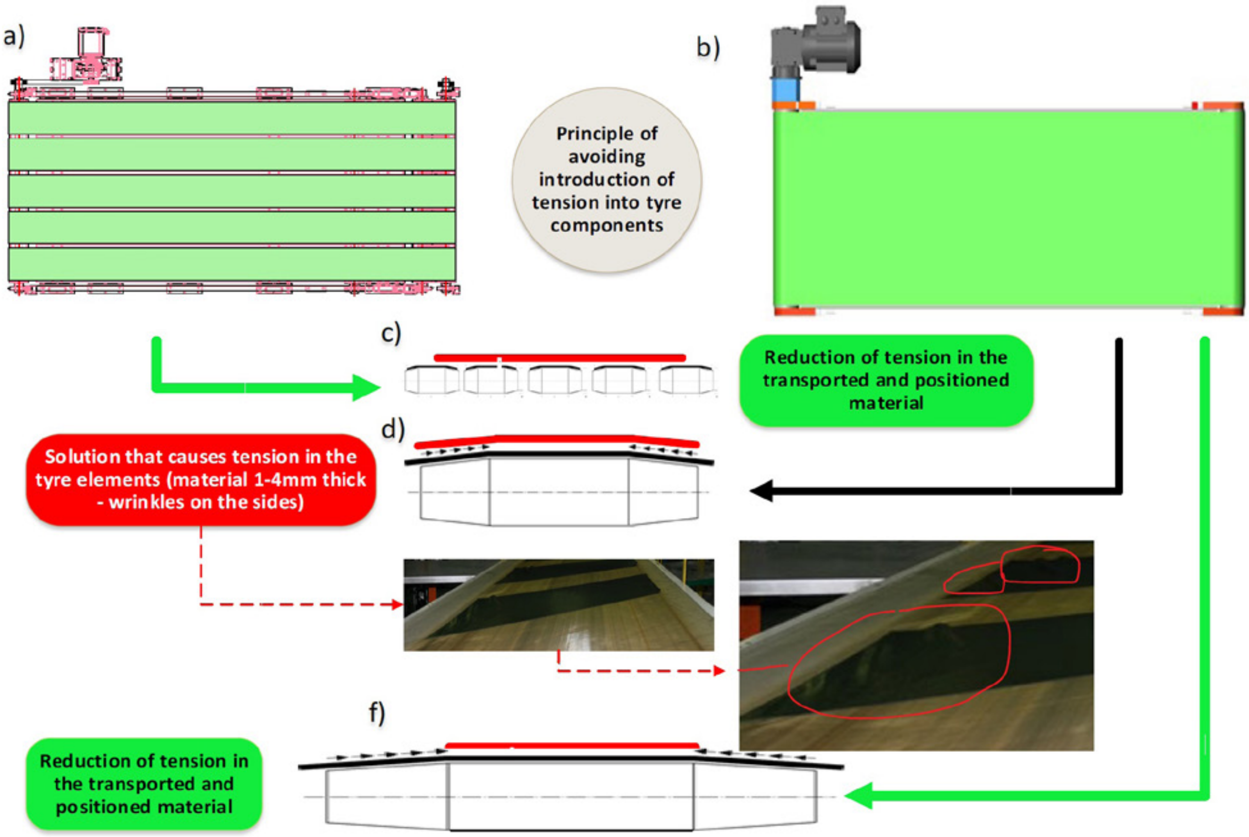

Fig. 13. Defining the minimum stiffness and dimensional stability of the components in order to determine the parameters required to avoid deformation of the tyre components. 11.a) Plastic and viscous components must be transported in the centre of a much wider conveyor belt. No deformation of the plastic component as a result of changes in the conveyor belt tension is allowed. For very fragile components, a steel belt and a thermal chamber with automatic ambient temperature control are used to keep the external environment constant; the tension is monitored by strain gauge measurements of the belt and the torsional moments measured on the rollers. 11.b) A system of several conveyor belts with rotational speed synchronisation and torque measurement reduces the adverse impact on the transported elements. The described solution improves the feeding precision and reduces the deformation of the plastic element caused by the tension of the monolithic belt. The presented solutions can be used interchangeably [own elaboration]

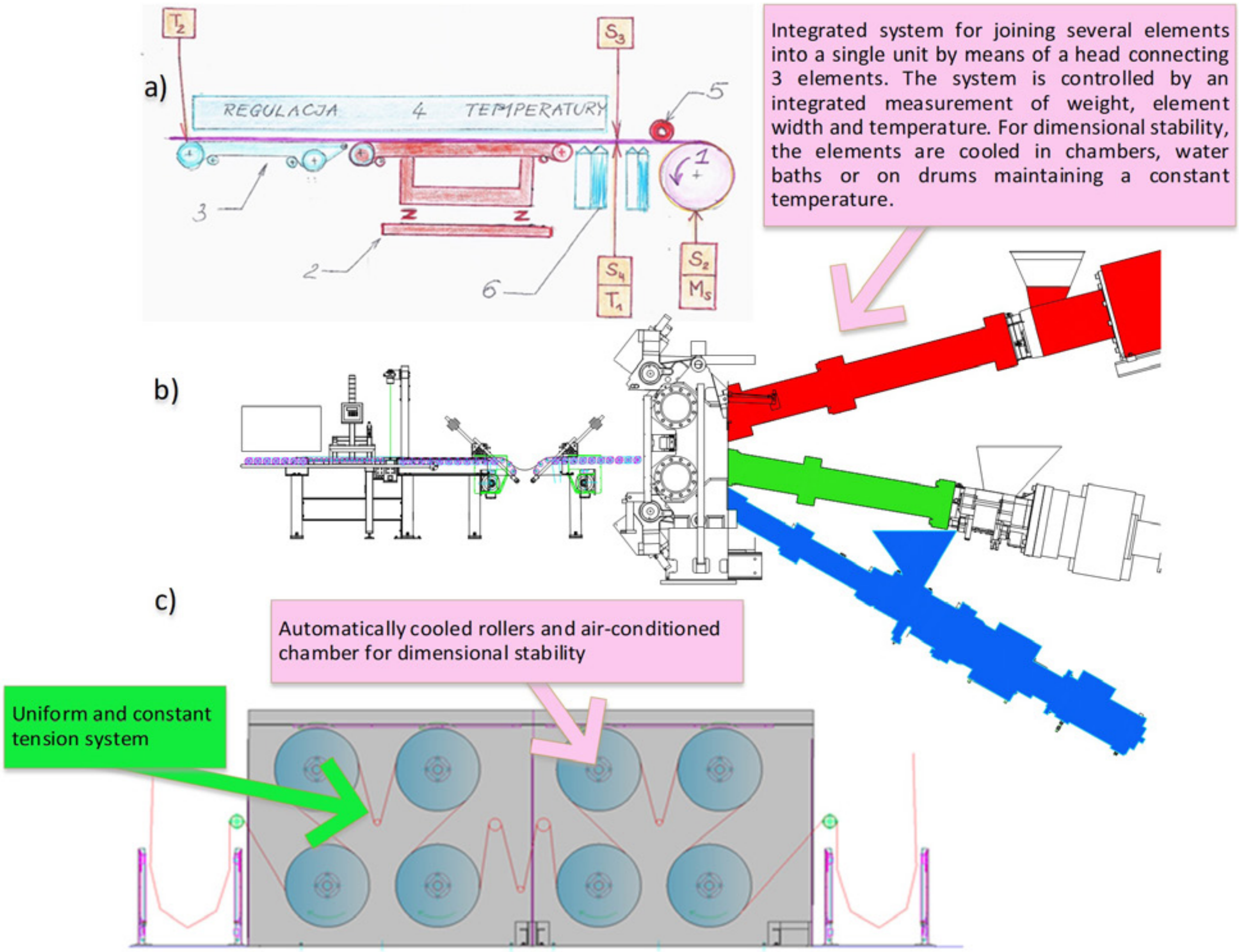

Fig. 14. The use of the parameters of mass, shape, temperature and pressure to automate process control. During the tyre assembly process, many components are wound and unwound. 14.a) As the diameter of the wound material on roll 1 changes (measured with sensor S2), the unwinding speed must change accordingly. In order to automate such processes, drive systems which allow for precise measurement of the torsional moment Ms should be used. Another important parameter in the process of automation of such operations is the ongoing measurement of the material weight 2. Reduction of the weight of the material indicates stretching of the element, while its increase signifies material pile-up. Based on this data, the unwinding speed and linear speed of the conveyor belt 2 and 3 can be controlled and verified. In order to keep the conditions constant, this process should take place under constant temperature conditions (e.g. under a thermally insulated cover 4). Temperature sensors T1 and T2 make it possible to correct the air exchange settings inside the transport space 4. In order to avoid slippage between the tyre components and the belt - encoders 5 are used to measure the speed of the transported element, which is compared with the measurement of the linear speed of the conveyor belts. Slippage of tyre elements in relation to the belt is an undesirable phenomenon as it introduces tension between the layers of tyre components. The transported element should have as many support points as possible, which is why conveyors (3) with a small radius of rollers are used or systems of air nozzles supporting the rubber element from below and reducing the electrostatic charge (6). 14.b) Example of a head design: 3 tyre components controlled by a scale measuring 1 metre of extruded length, a shape sensor, a pressure sensor set inside the extrusion head and a temperature sensor. All these parameters are interrelated and influence the speed of extrusion and compound extraction from the pallet. 14.c) Extruded and calendered components made of rubber compound are subjected to thermal stabilisation on rotating drums in air-conditioned chambers, on conveyors in cooled chambers or in a water bath in the case of thicker sections [own elaboration]

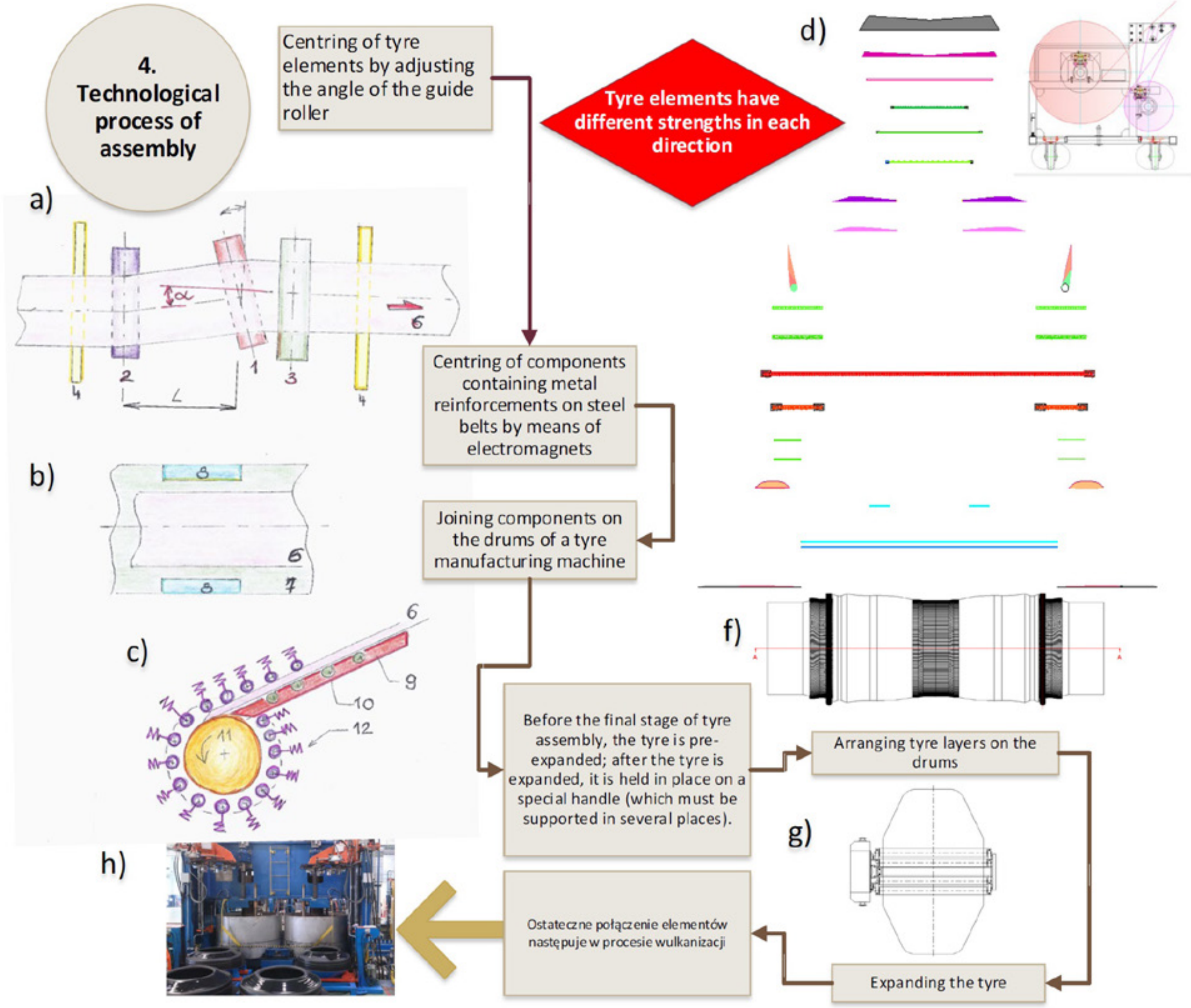

Fig. 15. Use of geometrical alignment of rollers and magnetic field for positioning of metal elements. 15.a) Steel and textile tyre components have high strength in one direction specified by the constructor; in other directions the components, even after reinforcement, still have relatively low tensile strength. Compounds covering steel and textile cords are characterised by high viscosity. For this reason, they cannot be directed to the bumpers in the same way as rigid bodies. In order to properly position cord-reinforced tape, it is necessary to use a roller or a set of rollers 1÷3. Setting the proper position of the roller 1. Two sensors 4 are used to constantly measure the position of the tyre component and correct the settings of the roller 1 in such a way so that the central axis of the tyre component measured by the second sensor 4 coincides with the central axis measured by sensor 4. The greater the distance L, the smaller displacement of roller 1 is required. 15.b) A tyre component reinforced with a steel cord can be positioned by means of elements 8, which generate a magnetic field to centre the tyre component 6 on the perforated belt 7. 15.c) The tyre component 6 slides due to gravitational force down the roller conveyor 10 and rests on the drum 11 of the tyre manufacturing machine, which can be held and pressed by means of pressure rollers 12 of a spring mechanism or pneumatic actuators. The element 9 may provide additional support to the component by means of a vacuum system or, in the case of steel elements, an electromagnetic system. 15.d) Example of a tyre made up of 31 units wound on carriages (this example shows the complexity of the assembly system). 15.f) The layers are placed on drums and the machine design is always adapted to the assembly technology. If more components are combined prior to the direct assembly process, the latter becomes simpler. 15.g) Example of tyre shape after expanding. The tyre must be supported in several places and is usually placed on racks, which should support the largest possible surface of the tyre. 15.h) The layers of the tyre are finally joined together in the vulcanisation press [own elaboration]

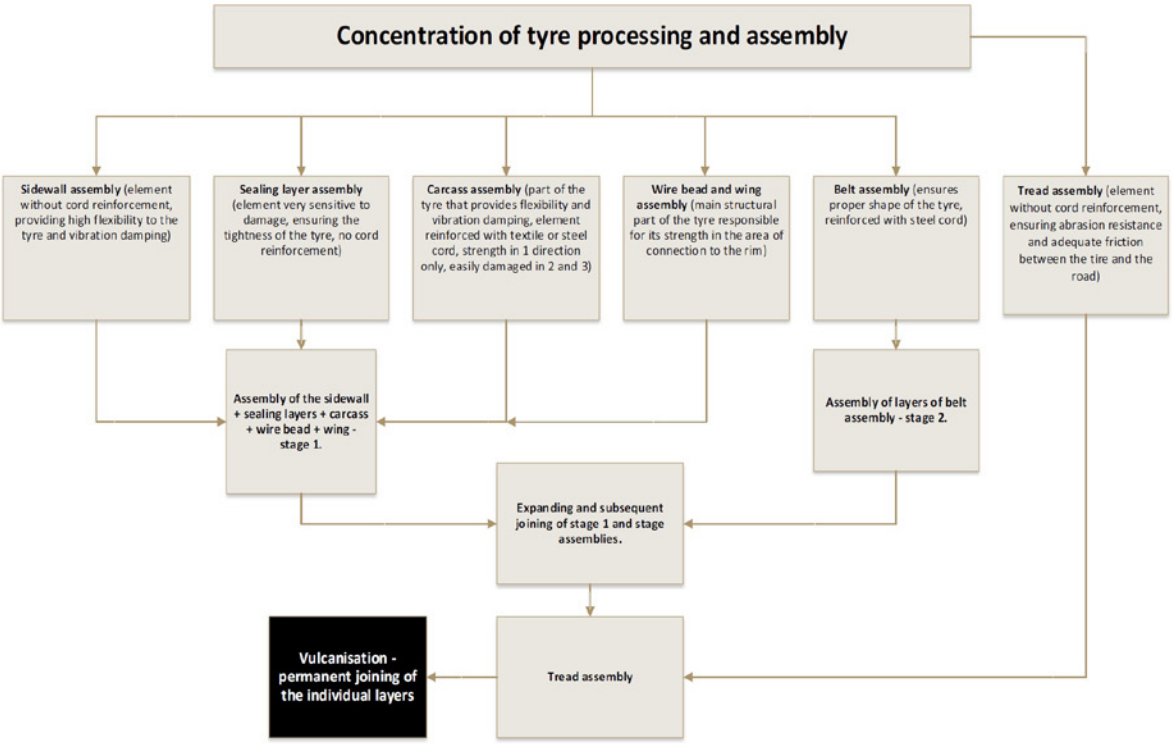

Fig. 16. Concentration of raw material processing operations in pre-assembly processes [own elaboration]

Conclusions

Automation and robotisation is the key to business success for companies manufacturing products with various levels of complexity. Automation and robotisation of processes guarantees repeatability of operations and their stable quality in the long term. The technology of rigid bodies assembly cannot be directly applied to the assembly of tyre components. According to the author of the paper, ***the technological process of tyre assembly*** *consists of identifying the physical and geometric features of the joined elements in order to determine assembly parameters and to select specialist tooling different from the conventional tools used in classical mechanical engineering assembly technology*. The presented paper allows us to identify the differences between the processes of conventional assembly and automatic assembly of tyres.

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