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MODELING AND SIMULATION OF THE BABY DIAPER PRODUCTION SYSTEM USING COLORED PETRI NET

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Abstract. *The lack of effective control of the diaper production process implies production loss, waste generation, and environmental impact. This paper proposes a novel approach to characterize the diaper converting machine as an intelligent resource within the context of Industry 4.0. We developed an intelligent control architecture to optimize the unwinder process, which will be automated and integrated with the production system, such as Manufacturing Execution System (MES) and Enterprise Resource Planning (ERP). This characteristic allows the control system to perform different activities collaboratively and precisely to optimize the use of raw material reels. This paper proposed Petri Net (PN) to describe the converting machine control system. We used the Colored Petri Net tools (CPNTools) to simulate and validate the proposed approach. The simulation of the model allowed analyzing different control strategies and compare the existing control system with the proposed new architecture approach. To illustrate the main advantage of this approach, we modeled and simulated a baby diaper converting machine installed in an industry in Brazil. The results show that it is possible to reduce a large amount of waste per year.*

Keywords: *Production System; Baby Diaper Converting Machine; Modeling by Colored Petri Net tools.*

1. INTRODUCTION

In recent years, the high level of informatization in control systems promotes a profound transformation of industrial production systems, driven by an intelligent, collaborative, and distributed production system. The fundamental concept within this context is Industry 4.0. It uses emerging technologies to integrate the business and its respective engineering processes into an operative, flexible, efficient, sustainable, high quality, and low-cost production system (Machado et al. 2020). According to Bonvoisin et al. (2017), sustainable manufacturing aims to ensure that production is carried out with an economy of resources, guaranteeing social standards. According to data from the European market, there are market opportunities in the premium infant diaper project in the specific case of the manufacture of infant diapers. These opportunities are related to improving its life cycle cost and eco-efficiency within a circular economy concept. This concept implies reducing waste or waste to a minimum through reuse, renovation, and recycling existing materials and products (Mendoza et al., 2019). This article focused on improving the infant diaper production process.

We presented a proposal for a distributed architecture for the infant diaper converting machine's raw material unwinding system. Each component that makes up the control system is considered an intelligent resource (Lee et al., 2015). The diaper converting machine is the equipment that receives and processes various types of raw material (polyethylene film, cellulose, super absorbent polymer (SAP), and non-woven). Each raw material has an independent input into the machine, entering through a linear and continuous process. Raw materials based on non-woven fabric and polyethylene are supplied in reels and fed to the device through unwinders. Materials are grouped and positioned on a central chassis, where the manufacturing process takes place.

The lack of effective control of the diaper production process implies production loss, waste generation, and environmental impact. This paper proposed a novel approach to characterize the diaper production process in an Industry 4.0 context. We consider the primary control components as intelligence resources. This characteristic allows the control system to perform different activities collaboratively and precisely to optimize the production process. In this paper, the intelligence resources are based on a fuzzy logic algorithm to maximize the use of raw material reels. Values of the continuous variables such as the angular and tangential velocity of the raw material reels, tension control, and discrete states define the state of the diaper production process. An asynchronous message exchange performs the collaboration of the intelligence resources. We use a publish/subscribe architecture to establish the communication between the multi-agent productive system, including intelligent unwinder resource, programmable logic control (PLC), MES, and ERP

(Rodjko, 2017). It is important to emphasize that the PLC is used. We use Colored Petri nets to specify and simulate the discrete and continuous behavior of the control devices and the communication between them.

Figure 1 shows a baby diaper converting machine. This machine receives the raw material through 7 modules: five raw material unwinders (cellulose, non-woven, polyethylene + non-woven back sheet, and lycra), one Super Absorbent Polymer Dozer (SAP) installed in the forming wheel module, and one hot melt system (seated behind the machine, not showed). Figure 2 shows the detailed main components of the unwinder raw material, which is the object of this paper.

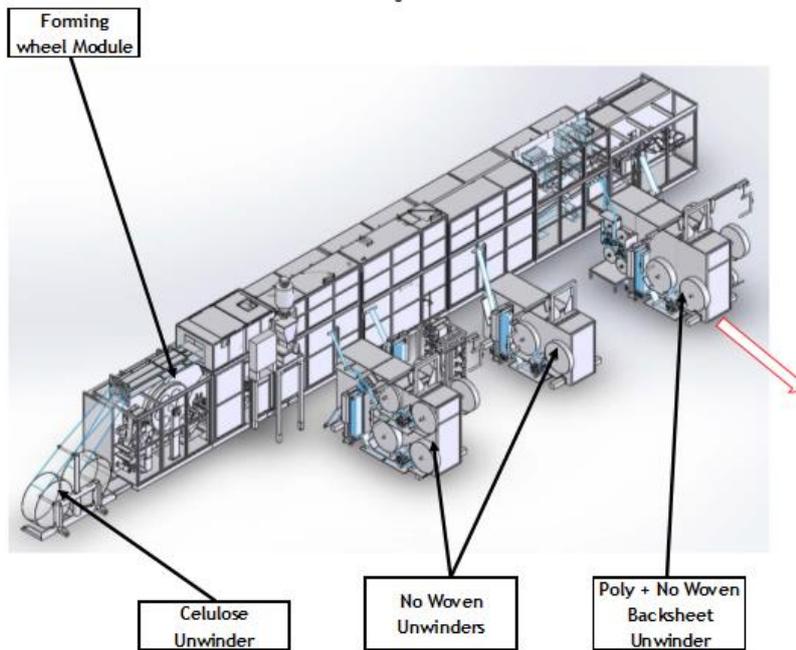


Figure 1 – Baby Diaper Converting Machine (www.zuiko.co.jp).

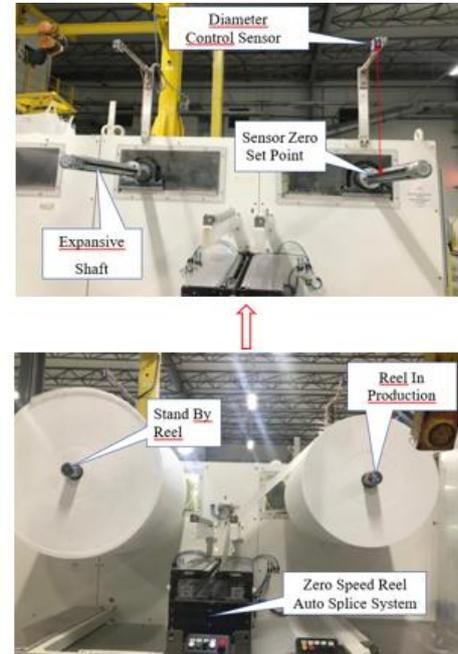


Figure 2 – Unwinder details

We divided this article into six chapters. Chapter 2 presents the new intelligent control architecture for raw material unwinders within the industry 4.0 concept. Chapter 3 addresses the research methodology used. Chapter 4 deals with the case study of the loss of raw material in unwinders. Chapter 5 presents the results. Chapter 6 presents the main conclusions.

2. PROPOSED ARCHITECTURE OF THE INTELLIGENT UNWINDER SYSTEM

Although the control system of a baby diaper converting machine has a high complexity, there is no effective control of the raw material unwinding process. This peculiarity represents a challenge to optimize the consumption of raw materials used to manufacture baby diapers. With proper management and monitoring, it will be possible to reduce the waste generated during the manufacturing process. The current unwinding process is carried out through a Programmable Logical Control (PLC) to feed a baby diaper converting machine (Pereira et al., 2021). This centralized control system performs the following features:

- measurement of the initial and final (theoretical) diameter of the coil, through a laser sensor that calculates the distance of the material;
- control of raw material speed and tensioning during the unwinding stage;
- automatic coil replacement based on theoretical final diameter. This feature does not allow to optimize the use of the raw material contained in the coil.

It is noteworthy that, in the current control system of the diaper converting machine, the control logic is centralized in the PLC. This characteristic makes timely data communication difficult for the decision-making levels of the MES and the ERP. Another feature is that there is no effective control of the coil diameter according to the variation in the grammage of the raw material. The Proportional Integral Derivative (PID) is currently used only to read the coil diameter through an incremental factor (Soltesz et al., 2016).

In this work it is proposed a distributed architecture of the intelligent unwinder control system for the baby diaper converting machine, with the following characteristics:

(a) Control of physical variation in the thickness tolerance of the raw materials, allowing self-adjustment and effective process control through an algorithm to optimize decision-making; (b) Using the sensors in specific machine points to optimize the algorithm proposed in item A.

The implementation of the characteristics mentioned above is based on using a heterarchical architecture, where the agents are distributed to control the productive system. These agents are autonomous and have functions independent of each other, with a defined interface that exchanges information to maintain the baby diaper production system. The algorithm to optimize the control logic will use artificial intelligence-based on fuzzy logic (Lima et al., 2019). The communication between the intelligent agents that constitute the distributed control will use the publish/subscriber communication paradigm (Diroi et al., 2020), aiming at the asynchronous and uncoupled communication between the agents to have in real-time the reel diameter updated. Figure 3 illustrates the new heterarchical architecture of the intelligent unwinder.

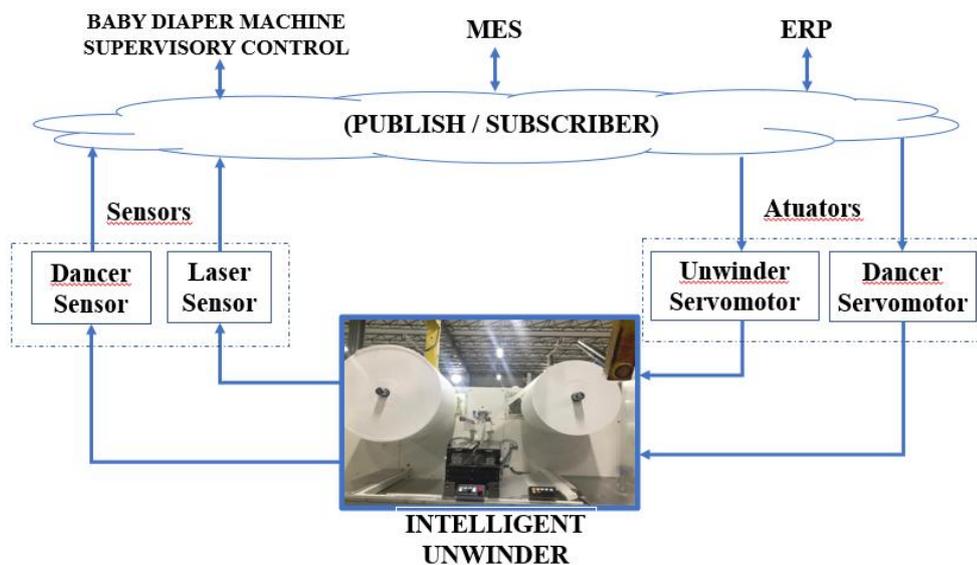


Figura 3 : New heterarchical architecture of the intelligent unwinder

The new distributed architecture has the following characteristics: optimization in real-time of the coil diameter reading by using fuzzy logic; the distributed control architecture facilitates the communication between the control devices and the MES, ERP, and supervisory agents; scalability, which enables the development of new functionalities without increasing the level of complexity of the control system; the publisher/subscriber paradigm allows the decoupled communication and distributed control between the agents; the diaper converting machine will be an intelligent factory floor resource, that is, autonomous, decentralized and connected in real-time with the decision-making levels of the business.

2.1 Agent.

It is an autonomous entity that can observe an environment through sensors and act on it through actuators. To make their decisions, they can work reactively, perform reasoning by symbolic algorithms. Intelligent Agents may also learn and use this knowledge to improve their performance (Stuart, 2002).

2.2 Colored Petri Net (CPN).

It was developed in 1987 by Kurt Jensen. It is a graphic and mathematical tool for analysis and system modeling. CPN provides a mathematical basis to study the dynamic properties of the model in addition to the particular characteristics of each system. It can represent the entire system functioning, facilitating modeling (Jensen, et al., 2007). Figure 4 illustrates CPN applied to model and simulate the sending of information from the laser sensor to the servomotors. The lecture of the sensor is represented by a token 160. This number represents the actual diameter of the reel (160mm). After transition "Diameter" fires, this token is sent to the places "Unwinder servomotor" and "Dancer Servomotors".

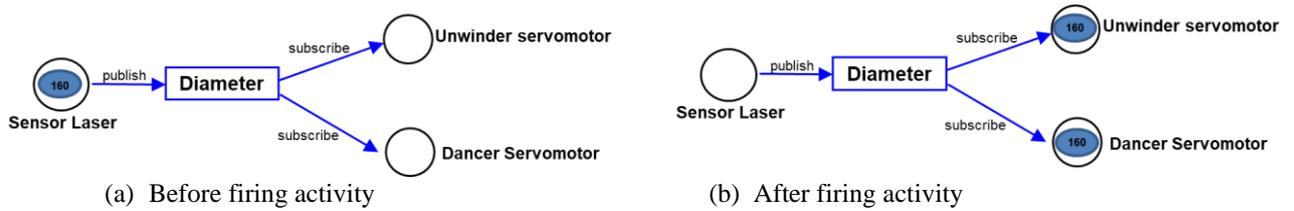


Figure 4: CPN applied on intelligent Unwinder.

2.3 Fuzzy Logic.

Lofti A. Zadeh created the Fuzzy Logic in 1965. In the '80s and '90s, Fuzzy Logic was widely used in the Japanese industry producing various household appliances and industrial solutions. Nowadays, it is currently used in applications involving artificial intelligence.

The Boolean Logic, which only uses values of 0 (Off/False) and 1 (On/True), that is, an element belongs or not to a group. Fuzzy logic uses the concept of partial truth, where every aspect has some degree of relevance in the groups involved, thus achieving to interpret values between 0 and 1.

The Fuzzy Logic uses non-linear and time-varying values, which allows it to be applied in flexible and intuitive systems to deal with uncertainties and inaccuracies. Furthermore, it can work with the uncertainty related to the meaning of words through linguistic variables or contextual information (Mendel, 2007). The basis of Fuzzy Logic is a set of pre-established rules. A Fuzzy Logic system contains the following components: fuzzifier, inference, rule base, and defuzzifier. These are related according to the information flow, as shown in Fig. 4 (Rizol.; Mesquita.; Saotome.; 2011).

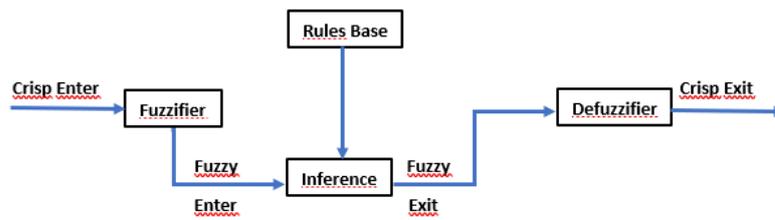


Figure 4. Fuzzy Logic information flow

Fuzzifier: After carrying out the request of the parameters, this component transforms the input data into fuzzy sets, which are data capable of gradually showing its relevance within a set. These sets are also known as membership functions. Then, the function with the degrees of the significance of contextual information is sent to the inference component.

Inference: It consists of checking the compatibility of the function received with the premises of each rule stored in the rule base. Each rule has an equivalent weight ranging from 0 to 1. At the end of the verification process, all the results are added to be sent to the defuzzifier.

Rules Base: It is formed by structures of the type "If" (premise or antecedent) and "Then" (conclusion or consequent). The rules are always related to raw material tension and speed in rotations per minute (rpm). Exemplifying: If the stress is high and the rpm is high, then the output increases rapidly.

Defuzzifier: This component receives information from the rules to obtain a single value to perform the control.

3. MODELING AND SIMULATION PROCEDURE PROPOSED.

We divided the modeling and simulation of the diaper converting machine into five steps described below.

Step1: System requirements

The first step is to describe the main features and functionalities of the diaper converting machine. In this step, it is essential the participation of the stakeholders involved in the project. We propose utilizing the Petri Net (PN) (Murata, 1989) as a modeling technique to describe the requirements of the control system conceptually. The PN model represents the processes and the unwinder system.

Step 2: Specification of the control strategies

In this step, we described all the activities and communication interfaces presented in the control system. The collaboration of the agents is performed by sharing the necessary information to implement the control strategies.

Step 3: Simulation of the essential components

In this step, the agents of the control system are simulated and analyzed by using the simulation software CPNTools (Kaneshiro.; Haghghi.;Ling.:2014).

Step 4: Structural modeling and simulation of the control system

At this step, all agents are integrated and simulated to develop the control system.

Step 5: Analysis of the control system

Once we developed all agents that integrate the control system, we analyzed the models by simulation. In this step, stakeholders involved in the project can review the procedure and improve the control logic of the diaper converting machine. The simulation allows the study of unexpected behavior and the discovery and test of new features not specified in previous steps.

4. CASE STUDY

To validate the approach proposed in this section, we presented a manufacturing process for baby diapers in the manufacturing industry in Brazil. This process uses a baby diaper converting machine with a centralized control architecture. The raw material coils used for the production of baby diapers have the following specifications and technical characteristics:

- The materials are based on No woven (polypropylene) and polyethylene film + No Woven (backsheet);
- The materials have weight variation per coil due to their manufacturing process, as shown in table 1;

Table 1: Weight variation by coil and by type of raw material

PHYSICAL CHARACTERISTICS BY RAW MATERIAL REEL BASED ON SUPPLIER TECHNICAL SPECIFICATION														
GRAMATURE ON GRAMAGE PER SQUARE METERS (gsm)														
PRELAMINATED BACKSHEET POLYETHYLENE + NO WOVEN			TOP SHEET NO WOVEN			LEG GAHTERS NO WOVEN			C-WRAP NO WOVEN			AQUISITION LAYER NO WOVEN		
MINIMUM	NOMINAL	MAXIMUM	MINIMUM	NOMINAL	MAXIMUM	MINIMUM	NOMINAL	MAXIMUM	MINIMUM	NOMINAL	MAXIMUM	MINIMUM	NOMINAL	MAXIMUM
21	23	25	10,8	12	13,2	11,7	13	14,7	11,7	13	14,7	36	40	44
LINEAR METERS														
PRELAMINATED BACKSHEET POLYETHYLENE + NO WOVEN			TOP SHEET NO WOVEN			LEG GAHTERS NO WOVEN			C-WRAP NO WOVEN			AQUISITION LAYER NO WOVEN		
3.700			13.000			13.500			13.500			1.400		

- The coils have initial and final diameter variation due to grammage variation, as shown in table 2;

Table 2: Coil diameter variation due to grammage variation by type of raw material

INITIAL & FINAL REEL DIAMETER BABY DIAPER RAW MATERIALS AMPLING FROM REAL PRODUCTION											
RAW MATERIAL	POLYBACKSHEET		TOPSHEET NO WOVEN		LEG GAHTER NO WOVEN		C-Wrap NO WOVEN		AQUISITION LAYER NO WOVEN		
	Initial Diameter	Final Diameter	Initial Diameter	Final Diameter	Initial Diameter	Final Diameter	Initial Diameter	Final Diameter	Initial Diameter	Final Diameter	
REEL DIAMETER (mm)	850	111	967	101	938	107	930	110	725	130	
	840	109	970	105	930	109	940	115	725	118	
	827	107	965	111	940	113	935	105	730	120	
	850	111	980	107	928	105	940	113	725	120	
	820	105	967	104	935	104	920	104	725	125	
	835	111	972	113	947	115	945	115	715	120	
	835	105	979	115	940	119	945	115	720	117	
	832	111	981	111	938	111	925	105	720	125	
	832	104	970	113	945	109	925	105	720	120	
840	104	980	101	920	104	920	104	715	125		
AVERAGE	836	108	973	108	936	110	932,5	109,1	722	122	
MINIMUM	820	104	965	101	920	104	920	104	715	117	
MAXIMUM	850	111	981	115	947	119	945	115	730	130	

Step 1: System requirements.

This first step describes the intelligent unwinder control system of the baby diaper converting machine. The main features are described below.

- Calculate the raw material unwinding speed based on the coil diameter, pre-selected tension, and linear velocity of the diaper converting machine.
- Adjust the speed of the spindle and balancer servomotors according to the calculated rate;

- Activate raw material accumulator when the final coil diameter is close to 101 mm;
- Carry out the automatic coil change when the coil diameter is close to 101 mm;

Figure 6 illustrates the application of the Petri net to describe the control flow of the diaper converting machine.

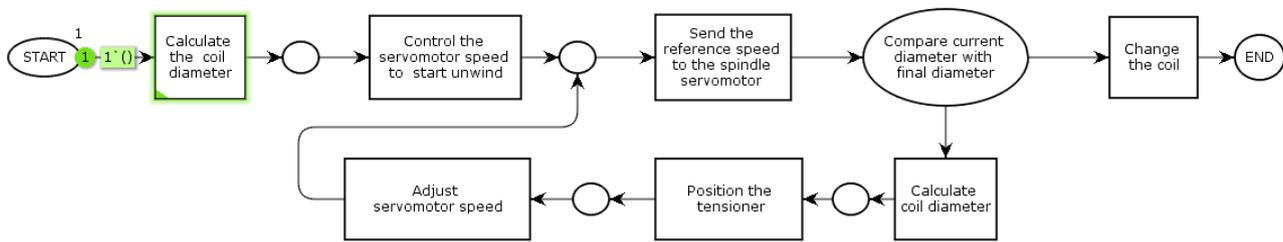


Figure 6: Petri Net representation of the Diaper Converting Machine

Step 2: Specification of the control strategies.

The intelligent unwinder uses the following modules to control the production systems:

A. Laser Sensor Module.

- Continuously reads the coil diameter;
- Publishes all diameter readings on the control networks;

B. Dancer Sensor Module.

- Continuously reads the tension of the raw material coil;
- Publishes the Accumulator position on the control network.

C. Servomotors Module.

- Subscribes the coil diameter data and adjusts the expansive shaft servomotor speed for continuous unwinding;
- Subscribes the coil diameter data, raw material tension data and adjusts the balance Servo motor speed to the ideal tension;

The distributed control system is integrated by three other agents, as presented in Figure 3.

Supervisory Agent:

- Subscribes data published by Laser and Dancer sensors;
- Performs the synchronization and sequencing of the servomotors that control the infant diaper converting machine;
- Monitors linear speed (m/min) and quantity of products per minute (ppm), according to the baby diaper size recipe to be produced.

MES Agent.

- Subscribes the data published by the Laser sensor;
- Updates actual raw material consumption data, as a function of coil diameter, production speed in linear meters per minute versus infant diaper size in production;
- Updates the number of diapers produced (compliant and non-compliant) based on the actual consumption of raw material.

ERP agent.

- Subscribes the data published by the Laser sensor;
- Updates actual raw material consumption data, as a function of coil diameter, production speed in linear meters per minute versus infant diaper size in production;
- Updates the number of diapers produced, finished product/nappy inventory delivered, and available raw material inventory.

Step 3: Simulation of the essential components.

In this step, we defined the new architecture of the intelligent unwinder to have the agent's functions performed. So it is specified the following contextual information: Baby diaper machine linear speed 500 meters/minutes (m/min);

Actual speed x coil diameter (from maximum 981 mm up to a minimum of 101 mm);

Coil diameter in millimeters (mm);

Ideal raw material tension (3 N/5cm);

Actual coil raw material tension (from 2 N/5cm up to 3N/5cm)*;

*ASTM D5035 standard methodology for No Woven material.

Figure 7 presents input/output interfaces to the intelligent unwinder control. This module is responsible for performing the adjust. This module controls the angular velocity of the servomotor to the unwinder.

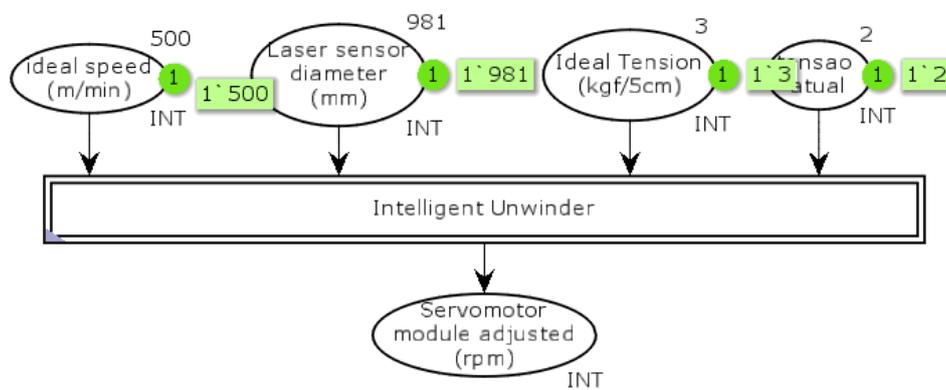


Figure 7: Intelligent Unwinder control.

At this step, the intelligent unwinding agent is built and modeled in the CPNTools tool (Kaneshiro et al., 2014) to simulate its operation using the Fuzzy logic. Figures 8A and 8B (detailing artificial intelligence applied on unwinder) illustrate the fuzzy logic applied in the intelligent unwinder and simulated in CPNTools, considering the defined contextual information:

linear speed (500 m/min);

actual diameter (981 mm);

ideal tension (3 Kgf/5cm);

real tension (2 Kgf/5cm).

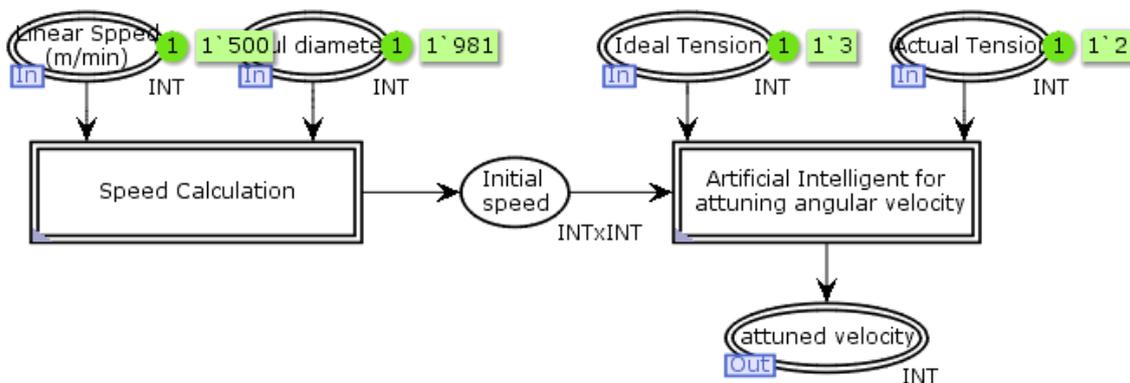


Figure 8A: Fuzzy logic applied in intelligent unwinder considering the contextual information

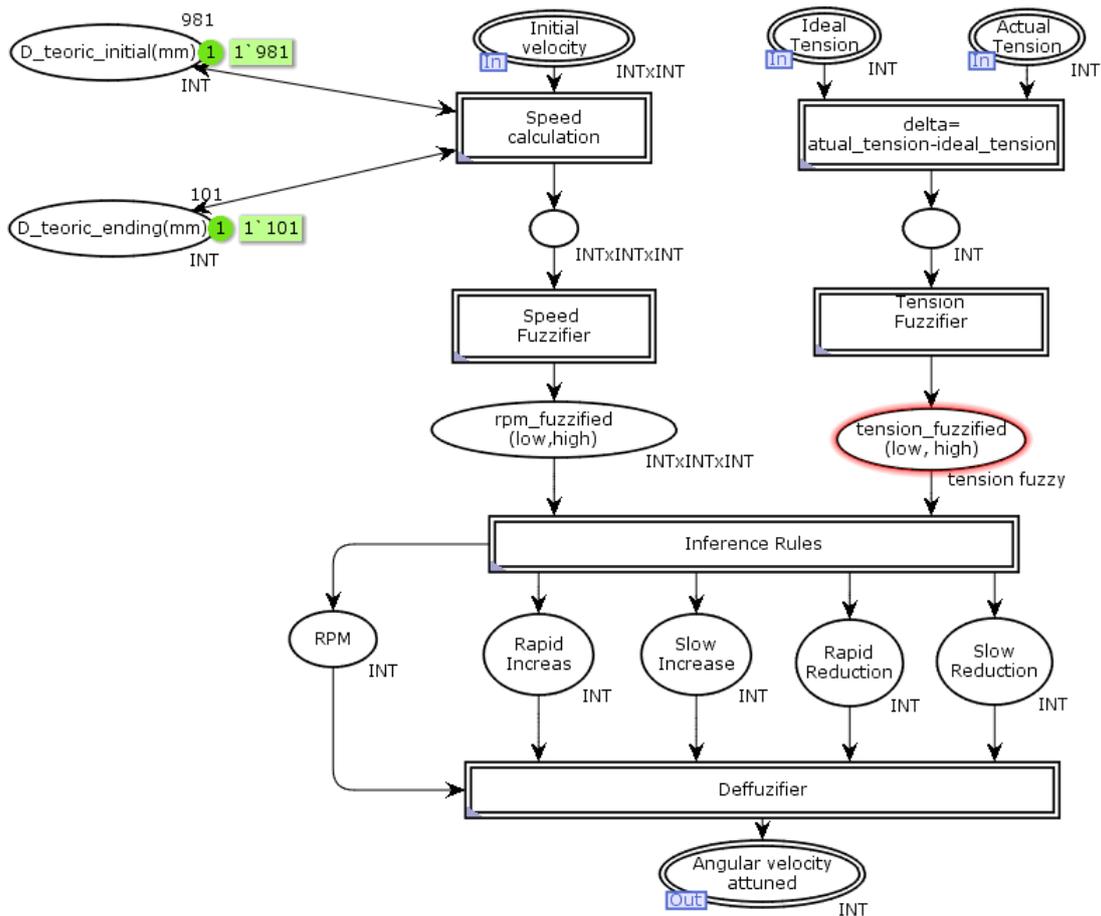


Figure 8B: Detailed Fuzzy Logic showing the artificial intelligent adjusting RPM process.

Figure 9 shows the Inference Rules applied on the Intelligent unwinder. For example, in Rule 1, if the tension is high and the angular velocity is high, then the angular momentum is increased rapidly.

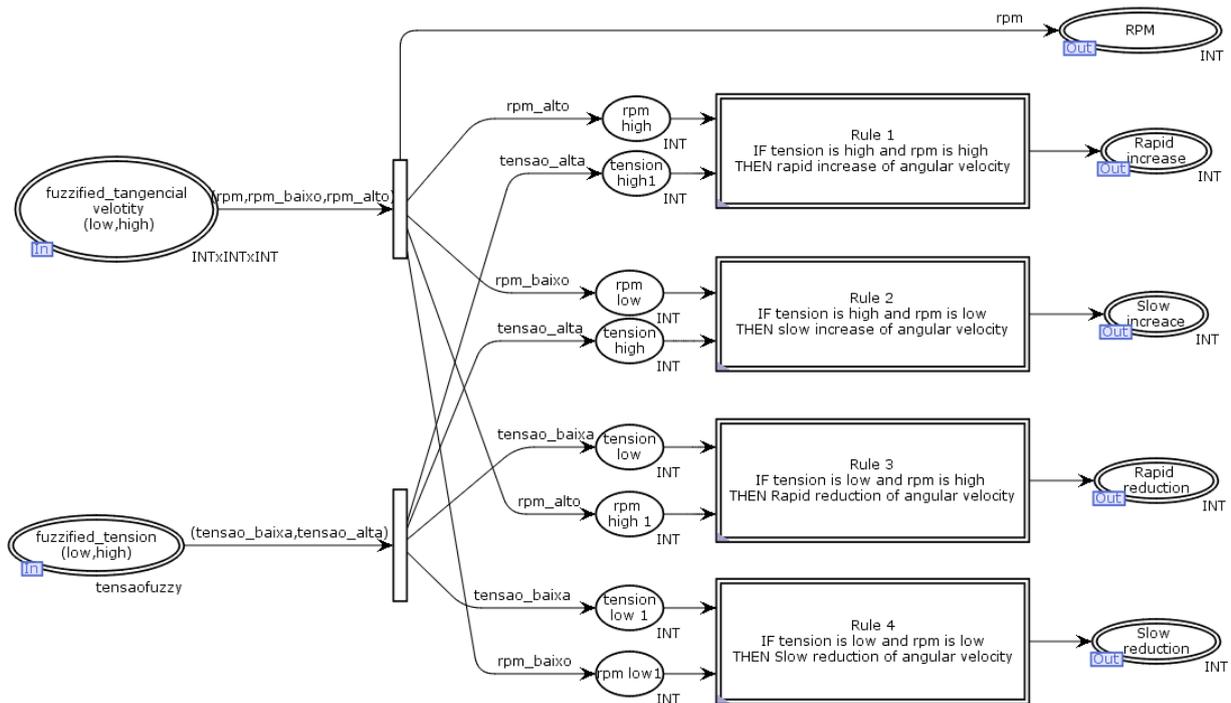


Figure 9: Inference rules applied in the intelligent unwinder.

Figure 10 illustrates the defuzzifier applied in intelligent unwinder. The defuzzifier module calculates the percentage of attuning of the tangential velocity according to the input parameters.

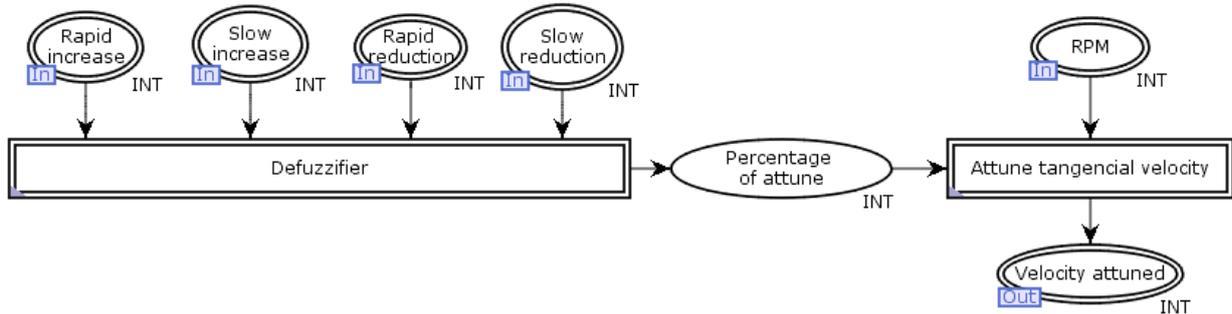


Figura 10: Defuzzifier model applied in the intelligent unwinder

5. RESULTS OBTAINED.

This research aimed to prove the following results:

- I. Validation of the new architecture by simulation using the CNPTools tool;
- II. Estimate the reduction of the physical amount of waste in tons/year (environmental aspect) and the respective financial savings, referring to the production process of baby diapers (economic part).

Figure 10 shows the estimated savings from raw material after applying the new intelligent unwinder architecture:

- the estimated annual savings of financial cost (financial aspect);
- the estimated yearly savings of waste (environmental factor).

ESTIMATED SAVINGS FROM NEW ARCHITETURE		UNIT
TOTAL ANNUAL WORLD WIDE BABY DIAPER MARKET CONSUMPTION	200	BILLION
HYPOTETIC NUMBER OF BABY DIAPER MACHINE RUNNING AT 500 M/MIN	400	UNITS
ESTIMATE FINANTIAL COST (POSSIBLE SAVING) (TOPSHEET + LEG GATHERS + POLYBACKSHEET + C-WRAP + AQL)	1.289.848	US\$ AMERICAN DOLLARS
ESTIMATED ENVIROMENT IMPACT (POSSIBLE SAVING) (TOPSHEET + LEG GAHTERS + POLYBACKSHEET + C-WRAP + AQL)	171	TONS

Figure 10: Estimated Savings from New Intelligent Unwinder Architeture.

6. CONCLUSIONS.

The proposal of a new architecture for accurate control of raw material consumption, applied in the unwinders of the baby diaper converting machine, will allow:

connectivity and continuous feedback, online and in real-time, between the factory floor (diaper converting machine) and the decision-making levels of the business (MES and ERP), within the context of industry 4.0;

elimination of the weekly physical inventory of planned x actual raw materials consumption, and the respective adjustment of the MES and ERP.

For the implementation of the new architecture, a total of 600 hours of software programming engineering is estimated, distributed as follows:

- 200 hours of programming;
- 200 hours of initial prototyping/field testing;
- 200 hours of improvement and final configuration of the software, the new architecture, and field test validation.

Assuming the person-hour cost of programming engineering, such as 1 hour = \$100.00, the estimated cost of implementing the new architecture will be \$60,000.00. Figure 10 shows that the new architecture will save an estimated US\$1.289 million per year and a reduction of 171 tons of waste/year, hypothetically considering:

worldwide installed park of (400x) infant diaper converting machines;

speed of 1,000 ppm (Large baby diaper size with 0.5 m in length);

It is then concluded that the payback of the new architecture will be two months, since:

Monthly Savings: US\$ 116,607.16 (= US\$ 1,289,848/ 12);

Required Investment: US\$ 60,000.00.

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REFERENCES

- Abebe, Diroi.; Haftu, Redai.; Naveen, Chilamkurti.; Abdun, Mahmood I.; Noor,Zaman.; Yunyoung, Nam. : Lightweight Authenticated-Encryption Scheme for Internet of Things Based on Publish-Subscribe Communication (2020). <https://doi.org/10.1109/ACCESS.2020.2983117>
- Bonvoisin, J; R. Stark; G. Seliger. 2017: Sustainable Manufacturing: Challenges, Solutions, and Implementation, (2017).
- Jensen,K., KristensenL.; Wells.L.; "Coloured Petri Nets and CPN Tools for modeling and validation of concurrent systems", *Internacional Journal on Software Tools Technology Transfer*, vol.9, no.3, pp.213-254, Junho, 2007.
- Kaneshiro, P.J.I., Haghghi, P.D., Ling, S. Situation-aware adaptation to optimize energy consumption in intelligent buildings using colored Petri nets. <http://ieeexplore.ieee.org/10.1109 / ICIEA 2014.6931164>, 2014.
- Lee.J.; Bagheri,Beharda.; Kao,Hung,An. A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing system. *Manufacturing letters*3 (2015) 18-23. <https://doi.org/10.1016/j.mfglet.2014.12.001>
- Lima, E. et al. Applying machine learning to ahp multicriteria decision-making method to assets prioritization in the context of industrial maintenance 4.0 *IFAC-PapersOnline*, Elsevier, v.52, n.13, p.2152-2157, 2019.<https://doi.org/10.1016/j.ifacol.2019.11.524>
- Machado, C.G.; Winroth, M.P.; Silva, E.H.D Ribeiro da. Sustainable manufacturing in industry 4.0: an emerging research agenda. *International Journal of Production Research*, Taylor&Francis, v. 58, n5, p. 1462-1484, 2020. <https://doi.org/10.1080/00207543.2019.1652777>
- Mendoza, J.M.F., Áponte, F.; Gualtieri, D.; Azapagic. A. Disposable baby diapers: Life cycle costs, eco-efficiency, and circular economy. *Journal of Cleaner Production*, Volume 211, 20 February 2019. <https://doi.org/10.1016/j.jclepro.2018.11.146>
- Mendel, J.M., "Uncertain Rule-Based Fuzzy Logic Systems: Introduction and New Directions," *IEEE Computational Intelligence Magazine*, vol. 2, no.1, Fevereiro, 2007. <https://doi.org/10.1109 / MCI.2007.357196>
- Murata, T. Petri nets: Properties, analysis, and applications. *Proceedings of the IEEE*, v.77, p.4,1989. <http://ieeexplore.ieee.org/10.1109 / 5.24143>
- Pereira.F.P.; Asato,O.; Kaneshiro, P.J.I.; Nakamoto, F.Y.; Proposta de Sistema de Produção de Fraldas Infantis: Recurso Inteligente com ênfase na Indústria 4.0 Sustentável. *Induscon* 2021.
- Rocha, P., Rizol, L.Mesquita, O.Saotome,"Lógica Fuzzy Tipo-2", *Revista SODEBRAS*, vol.6, no.70, pp.27-46, Outubro, 2011. <https://doi.org/10.13140 / RG.2.2.30241.84329>
- Rodjko, Andreja.; *Industry 4.0 concept: Background and overview. International journal of interactive mobile technologies (iJTM)*, 2017. <https://doi.org/10.3991/ijim.v11i5.7072>
- Russell. J.; Stuart.J.; Canny,. *Artificial intelligence: a modern approach* Second edition ed. Upper Saddle River, N.J.: [s.n.] pp. Chapter 2. ISBN 0137903952. OCLC 51325314
- Soltesz.K.; Grimholt.C.; Skogestad. S.; Simultaneous design of the proportional-integral, derivative controller, and measurement filter by optimization. *Institute of Engineering and Technology*, December, 2016. <https://doi.org/10.1049/iet-cta.2016.0297>