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A Supervision Approach based on P-time Petri Nets: Application to a coil winding machine

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Abstract —**Developments presented in this paper are devoted to the supervision based on P-time Petri nets (P-TPN) for manufacturing job-shops with time constraints. In such systems, operation times are included between a minimum and a maximum value. The P-TPN is used for modeling the normal behavior of the system by temporal spectrum of the marking. A new robust control strategy towards time disturbances is presented. The purpose of the proposed approach is to generate by the control a temporal shift similar to the disturbance in order to avoid the death of marks on the levels of synchronization transitions of the P-time Petri net model. A computing algorithm allowing the application of the proposed approach at various graph nodes is established.**

Finally, to demonstrate the effectiveness and accuracy of the monitoring approach, an application to a coil winding machine is outlined.

Keywords— **Robustness, time disturbance, detection, P-time PNs, coil winding machine**

I. INTRODUCTION

Manufacturing process, among other systems, uses some operations which duration has to be included into time intervals. The class containing textile manufacturing, food industries and chemical industries is particularly concerned.

The strict respect of the time constraint is mandatory, because a non-respect may produce a danger for some human or operator (healthiness in food industry, accident occurrences in time critical transport system for example). P-time Petri Nets are used to model and to monitor the system in order to respect time intervals and the robustness properties of the considered system.

The following work proposes a contribution to the field of monitoring and control of a coil winding unit. With an aim of improving the production quality, we develop a new supervisory strategy, able to react to abnormal situations. The suggested solution, in terms of failure detection, is based on the uncertainties study of processing times in workshops with time constraints. The processes control must guarantee, for each operation, the specifications of operational durations in order to ensure the conformity of the product and the production rate. Such systems have a robustness property in order to maintain product quality when there are time disturbances. The robustness is defined as the ability of the system to preserve the specifications facing some expected or unexpected variations. So, the robustness characterizes the capacity to deal with disturbances. In this context, the work presented attempt to build a robust control approach facing time disturbances.

The remainder of this paper is organized as follows. The second section uses the scientific literature to describe the position of the proposed approach in the state of the art. Afterward, the problem of supervision of manufacturing systems is tackled. An original approach based on P-time PN's and disturbances control is presented.

Section 4, presents the approach for robust control. This strategy consists of generating by the control a temporal shift similar to the disturbance in order to avoid the death of marks on the levels of synchronization transitions of the P-time Petri net model.

In the last section an academic example (coil winding machine) is then used to illustrate the different steps of the proposed approach. Finally conclusions and future studies are presented.

II. RELEVANT LITERATURE

PNs have evolved into a powerful and mature field of supervision research that enjoys wide applications in fields such as control [1], modeling, behavioral analysis [2] and decision aiding [3].

Li et al. [4], proposed a new approach for optimization of Reliability, maintainability and testability (RMT) parameters. First of all, the model for the equipment operation process is established based on the generalized stochastic Petri nets (GSPN) theory. Then, by solving the GSPN model, the quantitative relationship between operational availability and RMT parameters is obtained. Afterwards, taking history data of similar equipment and operation process into consideration, a maintenance model is developed.

Basile [5], introduced a model repair technique based on Timed Petri Nets. The paper focuses on temporal anomalies for Time Petri Nets (TPNs) models. The Goal is the model repair for timed DESs that can exhibit temporal anomalies. Temporal anomalies regard the duration of activities: they occur when an execution of an operation has duration different from the nominal one.

Hu et al [6] proposes an efficient method to design supervisors that enforce liveness and fairness for automated manufacturing systems (AMSs). A novel approach, which is based on the invariance property of Petri nets, was proposed to iteratively identify empty siphons as solutions to a set of linear inequalities. Supervisors are then designed to control these siphons. The authors shows that the liveness Enforcing allow to avoid the occurrence of deadlock situations to inhibit the emergence of partial or complete blocked for processing jobs in AMS.

Each one of these works has covered some aspects of supervision, however few works, nowadays, concern about how to use a combination of them to give a systematic procedure for supervision of manufacturing system with time constraints, as coil winding machine, using P-Time Petri Nets. Therefore, an original monitoring approach including the time constraints will be presented for the recovery of a winding unit.

Other researches consider the robustness control of manufacturing systems in order to save time and to ameliorate service quality.
Riera [7] presents an original approach for safe control synthesis of manufacturing systems. This approach is based on the use of a logic filter (placed at the end of PLC (Programmable Logic Controller)) robust to control errors, and formally validated using a model checker.

To model the robustness of manufacturing system in design, Gao [8] proposes a new approach. Firstly, a metric model for the index of manufacturing system robustness is built based on the information axiom and independence axiom of Axiomatic Design. Next, the quantitative computation approach of manufacturing system robustness by means of fuzzy theory is achieved.
Other control approaches and applications can be found in Mhalla et al. [9], Li al. [10], Yue et al. [11] and Wu et al. [12].

III . SUPERVISION TASK

The establishment of a supervision system is primordial. Its role is to recognize and to indicate in real time the behavior anomalies starting from information available on the system. Indeed the supervision task consists to detect diagnosis and correct failures. The general form of the proposed monitoring model, based on P-time Petri Nets, is shown in Fig. 1. Two models can be distinguished:

- Modeling and detection
- Control model

The two models are synchronized through the transmission and reception of failures symptoms S_i and control action U_i.

A. *Modeling and detection*

1) Presentation

The spine of the modelling task is the P-TPN. This model has an interface with the control process, Fig. 2. In this interfaces, any constraints violation is transmitted by an emission of a set of symptoms Si.

Definition 1:
The P-TPN associated to modelling model is defined as a n-pair: <P, T, Q, IS, F, S, M0>
where:
P= {p1, p2,… ,pn} : the set of places ;
T= {t1, t2,… ,tn} : the set of transitions;
Q= {q1, q2,…,qn} : the set of sojourn time;
IS = {IS1, IS2,…,ISn} defines the static interval of staying time of a mark in the place pi ;
S ={ S1 , S2 ,…, .Sn}: the set of fuzzy symptoms (signals) emitted by the modeling model (!Si) and received by the control process (?Si) from the studied discrete event system with time constraint;
M0 : is the initial marking of the network.

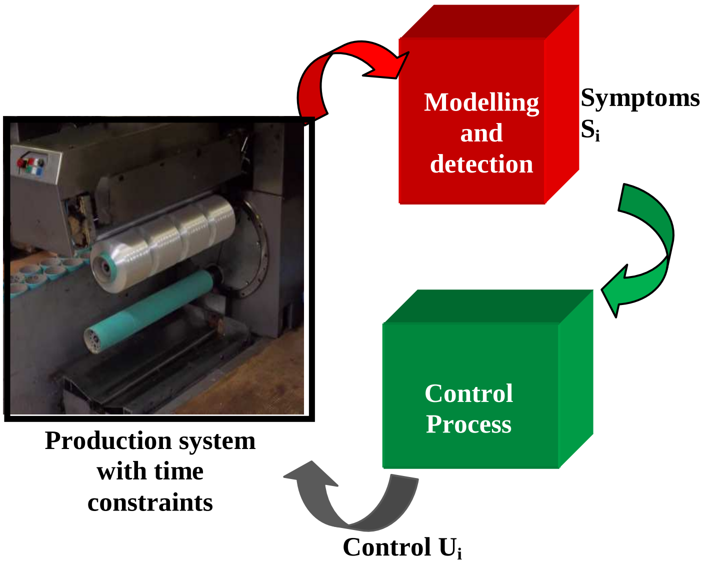


Fig. 1 General Form of Supervision Model

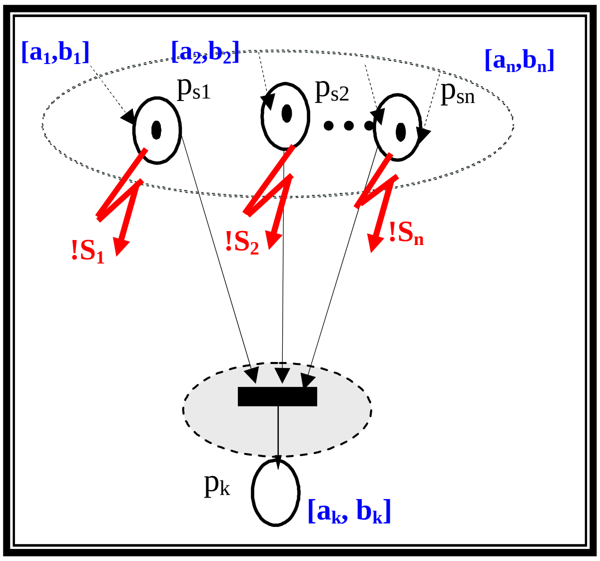


Fig. 2 Modelling and Detection model

In manufacturing workshops with time constraints, the time durations (operating or transfer durations for example) represent interval constraints. When the interval constraints are exceeded, there is an error.

An error is defined as a discrepancy between an observed or measured value and the true or theoretically correct value or condition [13]. In our study, an error means a gap between measured and computed time intervals by the scheduling task.

Based on the above statements, an error is sometimes referred as a failure synmtoms "S_i". Therefore diagnosis and maintenance action are taken when the system is still in an error condition, i.e. within acceptable deviation and before failure occurs.

B. CONTROL PROCESS

The first part performs some reminders on the definitions of robustness of the DES with time constrains. The second presents the approach for robust control. This strategy consists of generating by the control a temporal shift similar to the disturbance in order to avoid the death of marks on the levels of synchronization transitions of the P-time Petri net model

1)Basic definitions

Let us remember some definitions.

Definition 2 [14]: A mono-synchronized subpath SP_{TH} is a path containing one and only one synchronization transition which is its last node.

Definition 3 [14]: A perturbation Ω is locally rejected by a path "P_{TH}" if its last transition is fired as it is planned.

Definition 4: It is said that a path P_{TH} has a local passive robustness on $[\Omega_{min}, \Omega_{max}]$ if the occurrence of a disturbance $\Omega \in [\Omega_{min}, \Omega_{max}]$ at any place $p \in P_{TH}$ does not involve a token death at the synchronization transitions of SP_{TH}.

Definition 5: A temporal control is the modification of transitions firing instants using controlled P-time Petri net.

Definition 6: The transferable margin "δtr_k"on the mono-synchronized subpath "SP_{TH}" is defined as:

$$\delta tr_k = \min_{\substack{p_i{}^\circ = OUT(SP_{TH}) \\ p_i \notin SP_{TH}}} (H_i - q_{ie}) \qquad (1)$$

Definition 7: The passive rejection ability interval of a path "P_{TH}" is $PR(P_{TH})=[PRa(P_{TH}), PRd(P_{TH})]$ where:

$$PRa(P_{TH}) = \sum_{p_i \in P_{TH} \cap (R_N \cup Trans_{NC})} (q_{ie} - H_i), \qquad (2)$$

$$PRd(P_{TH}) = \sum_{p_i \in P_{TH} \cap (R_N \cup Trans_{NC})} (q_{ie} - L_i). \qquad (3)$$

$PRa(P_{TH})$ (resp. $PRd(P_{TH})$) is called the time passive rejection ability for an advance (resp. a delay) time disturbance occurrence.

Definition 8: The available control margin for an advance, CMa (p_i), and the available control margin for a delay, CMd (p_i), associated to the place p_i are defined as:

$$CMa : P \rightarrow Q^-$$

$$p_i \rightarrow CMa(p_i) = \begin{cases} L_i - q_{ie} \text{ if } q_i \le L_i \\ q_i - q_{ie} \text{ if } L_i < q_i < q_{ie} \\ 0 \text{ if } q_{ie} \le q_i \le H_i \end{cases} \qquad (4)$$

$$CMd : P \rightarrow Q^+ \cup \{+\infty\}$$

$$p_i \rightarrow CMd(p_i) = \begin{cases} H_i - q_{ie} \text{ if } q_i \le q_{ie} \\ H_i - q_i \text{ if } q_{ie} < q_i < H_i \end{cases} \qquad (5)$$

Definition 9: If a transition t is controllable ($t \in T_C$), it constitutes an elementary subpath locally controllable on $[\max(CMa(p_i)), \min(CMd(p_i))]$

$p^o{}_i=t$ $\qquad$ $p^o{}_i=t$

Notations

Let us denote by:

–T_C: the set of controllable transitions,

–T_O: the set of observable transitions,

– T_S: the set of synchronization transitions,

–T_P: the set of parallelism transitions,

– $t_i{}^\circ$ (resp. $^\circ t_i$): the output (resp. the input) places of the transition t_i,

– $p_i{}^\circ$ (resp $^\circ p_i$): the output transitions of the place p_i (resp. the input transitions of the place p_i),

– q_{ie}: the expected sojourn time of the token in the place p_i,

– q_i: the effective sojourn time of the token in the place p_i,

– $St_e(n)$: the n^{nd} expected firing instant of the transition t,

– $St(n)$: the n^{nd} effective firing instant of the transition t,

– $IN(P_{TH})$: the first node of the path P_{TH},

– $OUT(P_{TH})$: the last node of the path P_{TH},

– C_{ms}: the set of mono-synchronized subpaths,

– C_{se}: the set of elementary mono-synchronized subpaths.

2) Robustness approach: Generation by the control a temporal shift similar to the disturbance

To avoid the death of marks at the level of synchronization transitions, the developed strategy consists of generating by the control, on the parallel paths, a temporal shift similar to the disturbance. The aim is to search on a given parallel path, a set of controllable transitions. In these transitions, trying to generate by controlling a temporal shift of the same nature as the disturbance (delay or advance) paths. If the disturbance type is a delay (respectively advance) time, then the temporal shift will be a delay (respectively an advance) time obtained by changing the firing instants of controlled transitions belonging to the parallel paths.

3) Algorithm

Consider G the P-time Petri net model of the workshop and Ω

a delay time disturbance in p_i (node n), observed in a transition t ($t \in T_O$).

Let M_{pk} (respectively $M_{OUT(P_{TH})°}$) the set of mono-synchronized subpaths containing the place p_k (respectively $OUT(P_{TH})°$).

```
{
    F={Ω, OUT(P_TH)} (F is a doublet composed by the residue of the disturbance and the output node of the path P_TH)
    ∀ P_TH ∈ M_pk ⇒ Ω′=Ω−PRd (P_TH)
    If
      Ω′ > (H_i−q_ie)/ {p°_i∈T_S ∧ p_i∉ P_TH ∧ p°_i∈ P_TH }, there is a control problem on p°_i : Application of the control strategy allowing to generate a temporal shift, to the set of controlled transitions, similar to the disturbance
   Else
    Ω′ < (H_I−Q_IE)/ {P°_I∈T_S ∧ P_I∉ P_TH ∧ P°_I∈ P_TH }, we apply the same procedure for each element of M_OUT(PTH)°
      }
```

III. ILLUSTRATIVE EXAMPLE

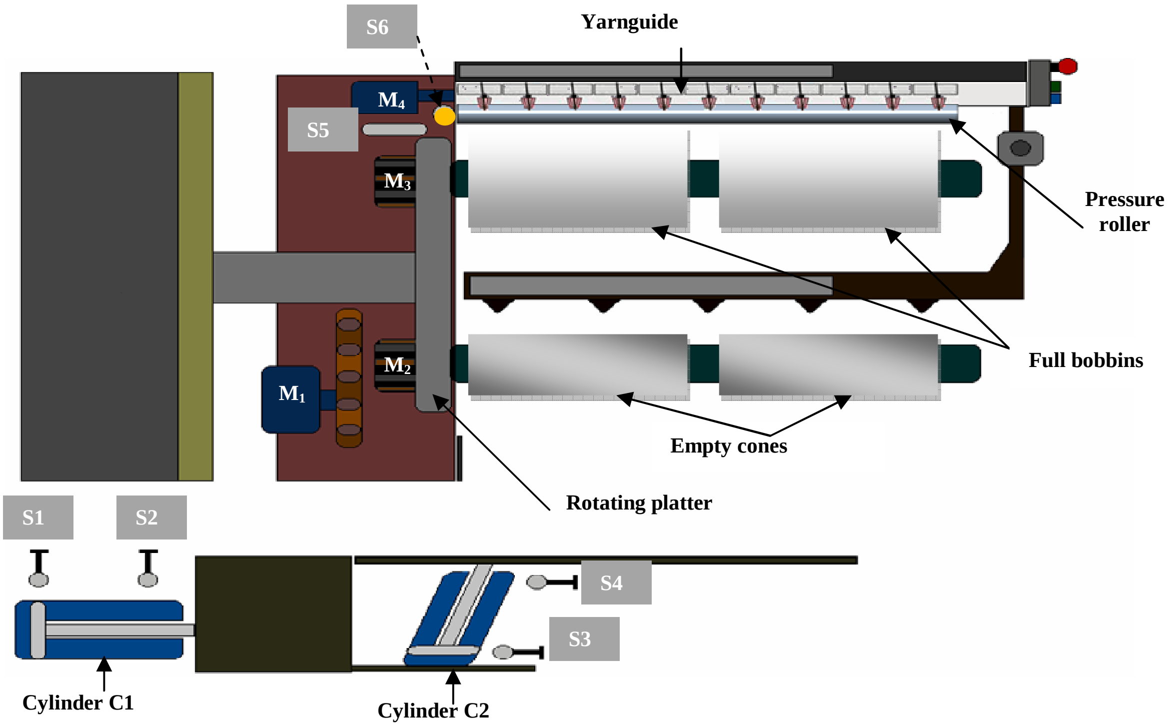
A. *Presentation of coil winding machine*

Winding machines are used heavily in textile manufacturing, especially in preparation to weaving where the yarn is wound on to a bobbin. In our study, the obtained bobbins are used for the production of fishing nets, Fig. 3.

The winder is responsible for winding the nylon filament, and evacuates the full bobbins. Once the winding operation is completed, the coils deviate from the pressure roller and the servo motor "M1" provides the inversely of the two brooches, Fig. 3. The lever arm is responsible for cutting the yarn. The full bobbins are then discharged by an evacuation trolly and a new winding operation is started.

B. *Modeling of winding machine*

In the studied workshops, a time interval is associated to each operation ($[L_i, H_i]$ with *u.t*: unit time). Its lower bound (L_i) indicates the minimum time needed to execute the operation and the upper bound (H_i) fixes the maximum time to not exceed otherwise the quality of product is deteriorated. Fig. 4, shows a P-time Petri net (G) modeling the production unit. The obtained G is used to study the robustness of the winding unit. The full set of time intervals of operations "IS_i" and effective sojourn time "q_{ie}", are summarized in table 1 (u.t: unit time second). The full set time intervals of clamping, winding, cutting and unloading are computed using the CPLEX 12.5 on a computer with Intel (R) at 2.16 GHz and 2 Go RAM.



$\mathbf{M_1}$: servo-motor ; $\mathbf{M_2}$, $\mathbf{M_3}$:Brooch motors; $\mathbf{M_4}$: Yarnguide motor; $\mathbf{S_{i=1,2...,6}}$: Sensors

Fig. 3 Components of the winding machine

TABLE 1: FULL SETS OF TIME INTERVALS

Place	Operation	Task	IS_i	q_{ie}
P1	Op1	**Clamping empty cones**	$IS_1=[1, 11]$	$q_{1e}= 5$
P2	Op2	**Winding**	$IS_2=[6600,7200]$	$q_{2e}=6780$
P3	Op3	**Yarn cutting**	$IS_3=[2, 5]$	$q_{3e}= 4$
P4	Op4	**Brooch inversion**	$IS_4=[2, 20]$	$q_{4e}= 5$
P5	Op5	**Motor braking**	$IS_5= [1, +\infty]$	$q_{5e}= 19$
P8	Op6	**Extending of pneumatic cylinder C1 (Sensor S2)**	$IS_8=[2, 4]$	$q_{8e}= 3$
P9	Op7	**Retracting of the pneumatic cylinder C1 (Sensor S1)**	$IS_9=[2, 5]$	$q_{9e}= 3$
P10	Op8	**Extending of pneumatic cylinder C2 (Sensor S4)**	$IS_{10}=[5, 9]$	$q_{10e}=8$
P11	Op9	**Retracting of the pneumatic cylinder C2 (Sensor S3)**	$IS_{11}=[3, 10]$	$q_{11e}= 7$

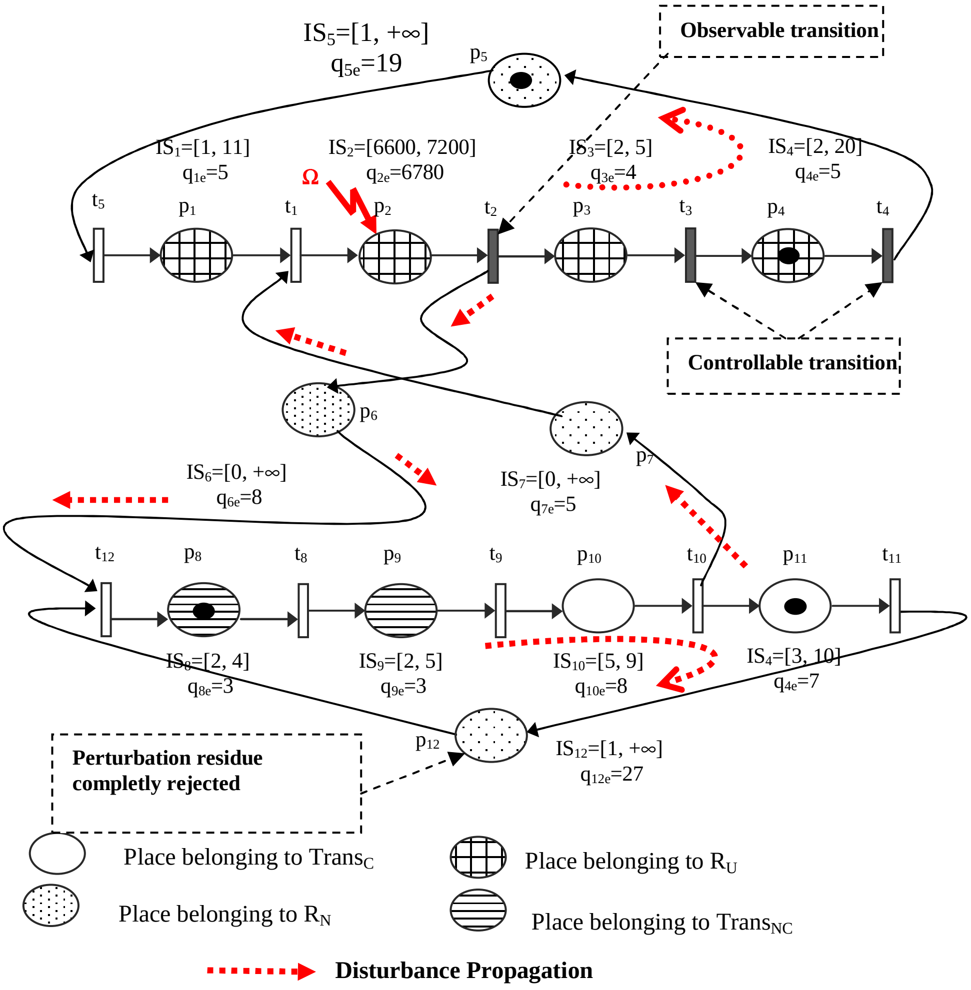


Fig. 4 Winding unit modeled by a P-time Petri net

C. *Functional decomposition*

As the sojourn times in places have not the same functional signification when they are included in the sequential process of a product or when they are associated to a free resource, a decomposition of the P-time Petri net model into four sets is made using [15]. The assumption of multi-product job-shops without assembling tasks as it was established:

While using [15], a functional decomposition of the Petri net model in four sets is established, Fig. 4, where:

- R_U is the set of places representing the used machines,
- R_N corresponds to the set of places representing the free machines which are shared between manufacturing circuits,

- $Trans_C$ is the set of places representing the loaded transport resources,
- $Trans_{NC}$ is the set of places representing the unloaded transport resources (or the interconnected buffers).

IV. APPLICATION OF THE ROBUSTNESS APPROACH TO A COIL WINDING MACHINE

In the studied workshop, the operations have temporal constraints which must be imperatively respected. The violation of these constraints can induce some catastrophic consequences. This example is a direct application of the proposed algorithm. Let Ω=23 a time disturbance in p_2, observed in t_2 (Fig. 4).

- The sojourn time of the token in p_2 is equal to 6803 ($q_2=q_{2e}+23$).
- The disturbance Ω is propagated towards the two paths $P_{TH1=}$ (t_2, p_3, t_3, p_4, t_4, p_5, t_5, p_1, t_1) and $P_{TH2=}$ (t_2, p_6, t_{12}) ($Mp_{2=}$[P_{TH1}, P_{TH2}]).
- On the path P_{TH1}, the disturbance is partially rejected in p_5 (PRd(P_{TH1})=18). The perturbation change passively the firing instant of the transition t_1 and also the sojourn time in the place p_1: $St_1(n)= St_{1e}(n)+5$ and $q_1=q_{1e}+5$. There is not death of mark on p_1 since we can accept a delay equal to 6 (IS_1=[1, 11]; q_{1e}=5)
- On the path Lp_2, the disturbance is partially rejected in p_6, and the mark is available in p_6 with a delay equal to 15 (PRd(P_{TH2})=8). Given the available control margin for a delay in p_{12} (CMd (p_{12})=+∝), a death of mark on the level of synchronization transition t_{12} is evitable.
- After the crossing of the transition t_{12}, the residue Ω'=15[$\Omega'=\Omega-$PRd(P_{TH2})] is transmitted to the two paths P_{TH3}=(p_8, t_8, p_9, t_9, p_{10}, t_{10}, p_7, t_1) and P_{TH4}=(p_8, t_8, p_9, t_9, p_{10}, t_{10}, p_{11}, t_{11}, p_{12}, t_{12}) through the starting place p_8 ($Mp_{8=}$[P_{TH3}, P_{TH4}]).
- On the path P_{TH4} , it is easy to check that the perturbation is completely rejected since the time passive rejection ability for a delay time disturbance is equal to 26 (PRd(P_{TH4})= 26).
- On the path P_{TH3}, the disturbance is partially rejected in p_7 (PRd(P_{TH3}) =5) and the mark is available in p_7 with a delay time equals to 10 (Ω"=10); there is a death mark in p_1 since the available control margin for a delay accepted is equal to 6 (CMd (p_1)= 6).

  – On the parallel path P_{TH1}, if the two transitions t_3 and t_4 are controllable ($t_3 \in T_C$, $t_4 \in T_C$) then they constitute two sub paths locally controllable respectively, on [-2, 1] and [-3, 15] (according to definition 11). So, by applying the proposed approach, we can generate a delay on the firing instants of the controlled transitions belonging to the parallel path of the propagation of the disturbance[($St_3(n)=St_{3e}(n)+1$) and ($St_4(n)=St_{4e}(n)+15$)]. As a result, the transition t_1 ($t_1 \in TS$) is fired normally and the death of marks on the levels of synchronization transitions is avoided.

■ Physical interpretation

The industrial sector is subject to numerous disturbing events which induce variations of the residence time initially computed by the scheduling layer. A temporal disturbance, exceeding the bounds of passive robustness, can cause a violation of constraints specifications. In P-time, this violation constraints is materialized by a death marks. In the winding machine, the detection of a constraint violation implies that there is a deterioration of product quality and a degraded production cycle (delay on unloading bobbins and production cycle).

In the studied example, we assumed that the winding operation is delayed (occurrence of a delay disturbance Ω on p_2). This delay is estimated to 23 u.t. The observed perturbation causes a delay on the level of evacuation operation (propagation of the disturbance to the paths P_{TH3} and P_{TH4}). The implementation of the proposed approach, which is consists to generate by the control, on the parallel paths, a temporal shift similar to the disturbance, allows compensating this delay. Indeed, the proposed approach consists to generate a delay on the execution of the two operations (cutting and yarn brooch). This lateness is manifested by a delay on the firing of the two transitions t_3 and t_4 on P-time Petri Net model (Fig. 4).

In conclusion, if the disturbance is a delay type, we generate, on the parallel paths, a temporal shift of the same nature as the disturbance (deceleration on cutting, inversion, retracting or extending of pneumatic cylinder,…). Consequently, both the death of marks on the levels of synchronization transitions and undesirable impact are avoided.

V. CONCLUSION

The proposed supervision mechanism integrates design models and safety analysis. Its purpose is to explain in details what is happening on the system and to help operators identifying failures in order to avoid a damage of the process or an accident with human beings.

The study of the robust control strategy facing disturbances in manufacturing workshops with time constraints, constitute the contribution of this paper. Controlled P-time Petri nets are used for modelling. Some definitions are quoted in order to build a theory dealing with such problem. They are illustrated step by step on a coil winding machine. The proposed robust control strategy tries to generate, on the level of controllable transitions a temporal shift of the same nature as the disturbance.

It is shown that the established strategy allows continuing the production in a degraded mode. This degraded functioning mode allows keep on producing while providing correct products.

It will be interesting to extend the application of the presented robust control strategy to transport networks. The study of the robustness of transport networks as DES would have a concrete assessment of the robust approach contributions. An important criterion for the evaluation of transport networks is stability. The latter is defined as the ability of a network to resume normal operation after the appearance of traffic perturbation (delay).

References

[1] H. Cam, , P. Mouallem et al. 2014. Modeling impact of attacks, recovery, and attackability conditions for situational awareness. IEEE International Inter-Disciplinary Conference on. Cognitive Methods in Situation Awareness and Decision Support (CogSIMA), Pp. 181-187.

[2] E. Morninga, H. Wakamatsu, E. Arai et al. 2014. Behavior analysis method for product design support a study on modeling of behavior and functions. IEEE International Conference on Electronics Packaging (ICEP), Pp. 736-739.

[3] O. Fouathia, J. Maun., P. Labeau et al. 2004. Stochastic approach using Petri nets for maintenance optimization in Belgian power systems. IEEE International Conference onProbabilistic Methods Applied to Power Systems, Pp. 168-173.

[4] T. Li, Y. Li, Y.Qian & Y. Xu. (2015). Optimizing reliability, maintainability and testability parameters of equipment based on GSPN. Systems Engineering and Electronics, Journal of, 26(3), 633-643.

[5] F. Basile, P. Chiacchio & J. Coppola (2015). Model repair of Time Petri Nets with temporal anomalies. IFAC-PapersOnLine, 48(7), 85-90.

[6] H. Hu & R. Su (2012). A novel approach to liveness supervision of AMS with assembly operations using Petri nets. In Control Automation Robotics & Vision (ICARCV), 2012 12th International Conference on (pp. 264-269). IEEE.

[7] B. Riera, D. Annebicque, F. Gellot, A. Philippot, R. Benlorhfar, Control synthesis based on logical constraints for safe manufacturing systems.*IFAC Proceedings Volumes*, *45*(6), 194-199, 2012.

[8] K. Gao, Y. He, Z. He & C. Gu, Reliability-Based Robustness Modeling Approach for Manufacturing System Design Based on Fuzzy Design Axioms. *8th International Symposium on Computational Intelligence and Design (ISCID)* (Vol. 1, pp. 619-623), 2015.

[9] A. Mhalla, N. Jerbi, S.C Dutilleul, E. Craye &M. Benrejeb. Robust control strategies facing disturbances in manufacturing workshops with time constraints. *Computers & Industrial Engineering*, *65*(2), 268-276, 2013.

[10] Z. Li, N. Wu & M. Zhou, Deadlock control of automated manufacturing systems based on Petri nets—A literature review. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, *42*(4), 437-462, 2012.

[11] H. Yue, K. Xing, H. Hu, W. Wu, & H. Su. Petri-net-based robust supervisory control of automated manufacturing systems. *Control Engineering Practice*, *54*, 176-189, 2016.

[12] Y. Wu, K. Xing, J. Luo & Y. Feng. Robust deadlock control for automated manufacturing systems with an unreliable resource. *Information Sciences*, *346*, 17-28, 2016.

[13] S. Yang AND T.S Liu: A Petri Net Approach to Early Failure Detection and Isolation for Preventive Maintenance. International journal of Quality and Reliability Engineering (1998), Vol.14, Issue 5, pp 319–330.

[14] N. Jerbi, S. Collart Dutilleul, E. Craye, and M. Benrejeb, " Time Disturbances and Filtering of Sensors Signals in Tolerant Multi-product Job-shops with Time Constraints", International Journal of Computers, Communications & Control Vol. I. No. 4, pp. 61-72, 2006.

[15] J. Long, "Flow Optimization Method for Control Synthesis of Flexible Manufacturing Systems Modeled by Controlled Timed Petri Nets"), IEEE International Conference on Robotics and Automation, Atlanta, Georgia, USA, vol. 1, pp. 598–603, 1996.