A Theoretical Approach of the Generalized Hybrid Model Based Control of Repetitive Processes

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Abstract—**A generalized Synchronized Hybrid Petri Nets (SHPN) model based control of a hybrid repetitive processes is presented in this paper. The whole process has two components: one discrete and one continuous. Its evolution can be described by a set of repetitive tasks. The generalized SHPN model is associated to this hybrid system with N repetitive tasks. The generalized SHPN model is customized to an assembly/disassembly mechatronics line (A/DML), served by a wheeled mobile robot (WMR) equipped with robotic manipulator (RM). The behavior as a hybrid system appears during disassembly, when WMR with RM is used to transport the work parts from the disassembly locations to the storage location in order to be reused in assembly. The assembly can be modeled as discrete system events (DES). This hybrid system takes into consideration the distribution of the necessary tasks to perform the hybrid disassembly of the work parts, by synchronization between WMR equipped with RM and A/DML. An optimization approach of the cycle time, associated to the control of repetitive processes is also presented.**

Keywords—assembly/disassembly; manufacturing line; wheeled mobile robot; robotic manipulator; Petri nets.

I. INTRODUCTION

This paper proposes a generalized Synchronized Hybrid Petri Nets (SHPN) dedicated to model the hybrid repetitive processes. The SHPN tool is involved to model the hybrid systems the evolution of which consists in a set of repetitive tasks corresponding to the elementary operations. To model the whole process, specific tools for both components, discrete and continuous, are necessary. These tools have to be adapted to the repetitive and synchronized tasks. The proposal will be tested for a reversible assembly/disassembly manufacturing line (A/DML) served by a wheeled mobile robot (WMR) equipped with a robotic manipulator (RM).

In this paper, the concepts of assembly/disassembly tasks are illustrated in the SHPN model which respects both aspects: the discrete approach of the elementary assembly/disassembly operations and the continuous approach of the displacement of WMR. The considered system is a hybrid one and requires specialized tools for modeling, as in [3]. The hybrid model is elaborated using the dedicated modeling tool, HPN, described in [9]and [10]. Combining the SED model of the analyzed system with the cyclic and continuous time of the WMR with RM results in a SHPN model. This paper is organized as follows: the description of A/DML served by WMR with RM and SHPN model in generalized and customized forms is presented in Section 2; the generalized and customized SHPN formalism is presented in Section 3. In Section 4, the SHPN model customised for HERA&Hortsmann mechatronic line is discussed. Section 5 is reserved to the optimization of the time cycle corresponding to the control of repetitive processes. Some conclusion remarks can be found in Section 6.

II. STRUCTURE OF THE A/DML SERVED BY WMR WITH RM

The assembly/disassembly line is served by a WMR equipped with RM during the disassembly phase. The objective is to make the assembly line reversible, i.e. to allow disassembly. Moreover, the mobile robot is used to carry the disassembled component to the proper storage warehouse. The general approach will customize an A/DML didactic HERA&Horstmann mechatronics line (shown in Fig.1a and 1b) that is designed for the assembly of a five components piece (shown in Fig.1c and Fig. 1d). The flexible line includes five individual workstations with different tasks: carrying and transporting, pneumatic workstations, conveyor belt, sorting unit, test station and warehouse. The assembly/disassembly manufacturing flexible line is equipped with SIEMENS Simatic S7-300 PLC (Programmable Logic Controller), with 5 distributed modules connected by Profibus. The WMR, Pioneer 3-DX, comprises of two driving wheels and one rear wheel has its own odometric system and an on-board embedded microcontroller that is able to read the position information and to send it through a WI-FI link to a remote PC that runs according to a specific protocol and sends the data to the PLC of the assembly line. The assembly/disassembly operation can be decomposed into a sequence of elementary assembly tasks coupled in parallel with the positioning tasks of the work-piece along the conveyor, as in [1], [2], and [4]. The hybrid disassembly strategy is based on the hierarchical model proposed in [5], [6], [7] and [8] which uses the general representation from Fig. 2. In Fig. 3, the schematic representation of the HERA&Hortsmann didactic platform destined to a particular assembly/disassembly product comprised of 5 parts and served by WMR with RM is presented. WMR carries the component from the place where disassembly occurs to the appropriate storage.

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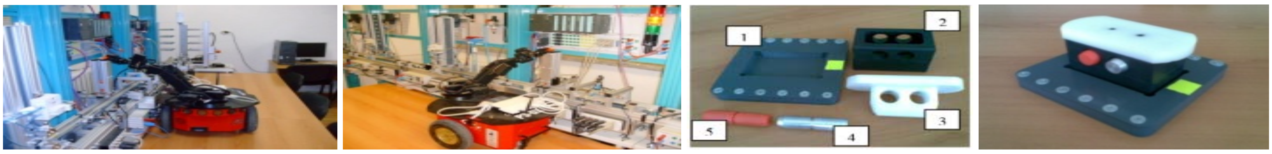

Figure 1. a) and b) assembly line, Hera, served by WMR, Pioneer 3-DX, equipped with RM, Pioneer 5-DOF Arm; c) parts; d) assembled product

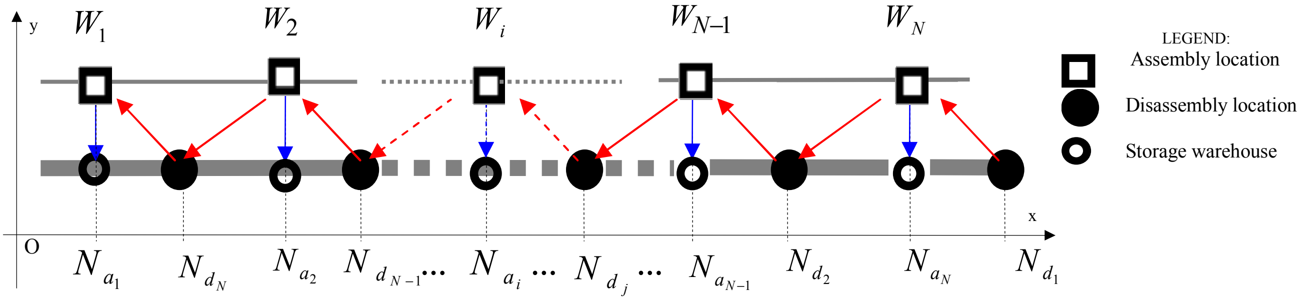

Figure 2. Assembly/Disassembly and storage warehouse locations

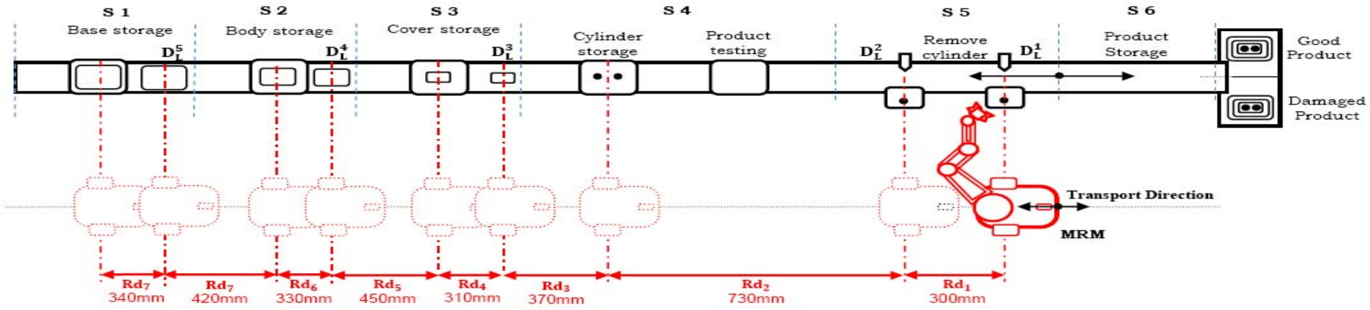

Figure 3. Assembly/disassembly line of a product consists of 5 components, served by the WMR equipped with RM

The SHPN structure from Fig. 4 is obtained through the modeling of the assembly/disassembly process and continuous service assistance for disassembly operations performed by the mobile platform equipped with manipulator. The entire model is SHPN type because it is interfaced with external synchronization events deriving from its modeling/simulation properties. The model is particularly useful in real-time control. The SHPN morphology results from theintegration of three PN models. Each of these models has a specific typology: TPN (Timed PN), SPN (Synchronized PN) and THPN (Timed Hybrid PN). These models describe the following automatic operations: • Assembling/storage in warehouses (TPN typology); • Disassembling of the damaged product (SPN and TPN typologies); • Service assistance during the disassembling process, performed by the mobile robot equipped with manipulator (THPN typology). $E^1_{dd(j)}$ and $E^2_{dd(j+2)}$ are external events received from the sensors used for line synchronisation with the WMR equipped with RM. $E^1_{dd(j)}$ is an external synchronization signal corresponding to STOPPING the line and STARTING the disassembly. $E^2_{dd(j+2)}$ is an external synchronization signal, corresponding to the PICKING UP of the disassembled component and the STARTING of the line. Fig.6 shows an elementary TPN model corresponding to an assembly operation. Fig.5 shows the generalised TPN model corresponding to the assembly process, which includes a sequence associated with the quality test for the end product. All of these can be modelled with a SHPN called elementary SHPN, represented in Fig. 7.

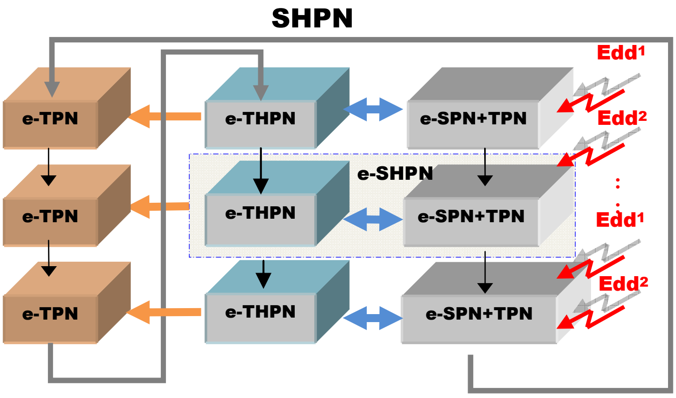

Figure 4. The SHPN representation by blocks with elementary modules:e-TPN for assembly, e-THPN for WMR with RM, e-SPN+TPN for disassembly and e-SHPN for disassembly served by WMR with RM.

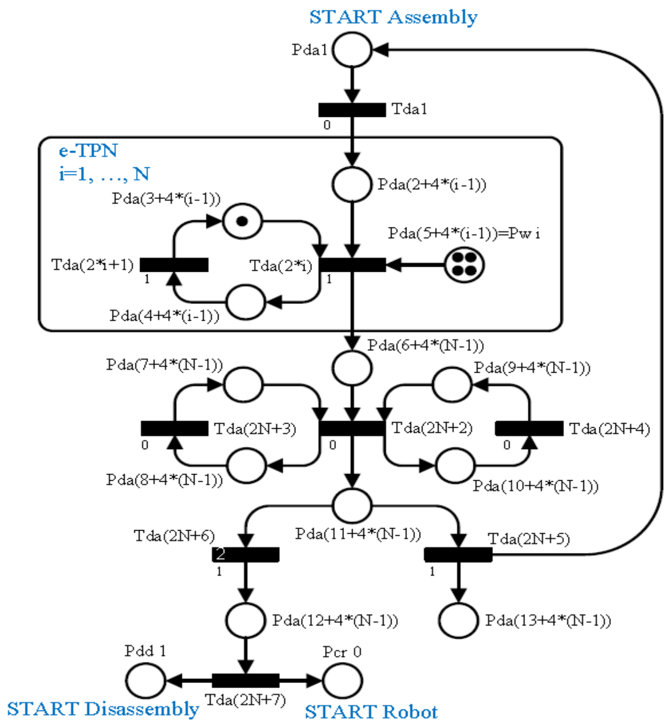

Figure 5. Generalised TPN model for the assembly process of N components

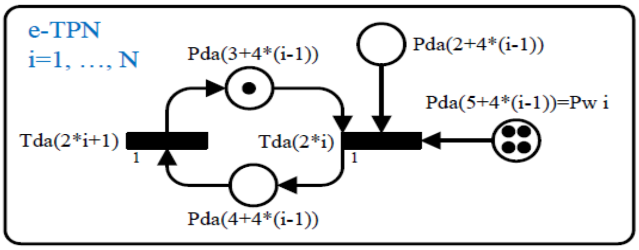

Figure 6. e-TPN model for an elementary assembly operation

Since after the last disassembly operation the starting line to a next disassembly is no longer necessary, the SHPN model is different from others as shown in Fig. 8. Let us consider the following notations:

- $N_{a_i}, i=\overline{1,N}$ - the assembly locations on the positive sense of Ox axis.
- $N_{d_j}, j=\overline{1,N}$ - the disassembly locations on the inverse sense of Ox axis. Obviously, $i=N-j+1$.
- $W_i; i=\overline{1,N}$ - the warehouse locations, that are identical to the assembly locations. Obviously, $W_{N+1-j}\equiv W_i, j=\overline{1,N}$.
- $D(N_{d_j}, W_{N+1-j})$ - the distance between disassembly location N_{d_j} and the corresponding storage warehouse W_{N+1-j}

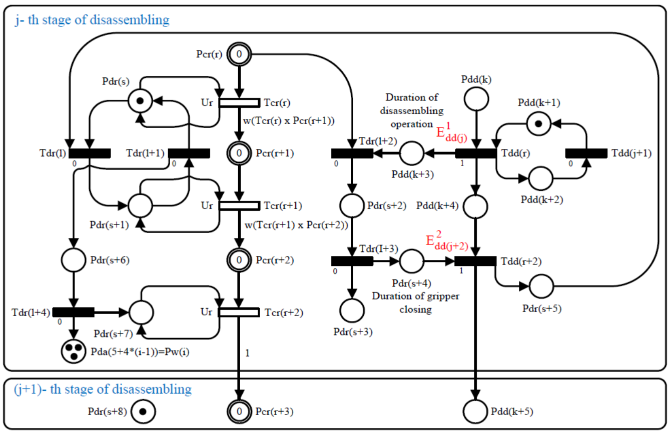

Figure 7. e-SHPN model of j-th elementary disassembly operation.

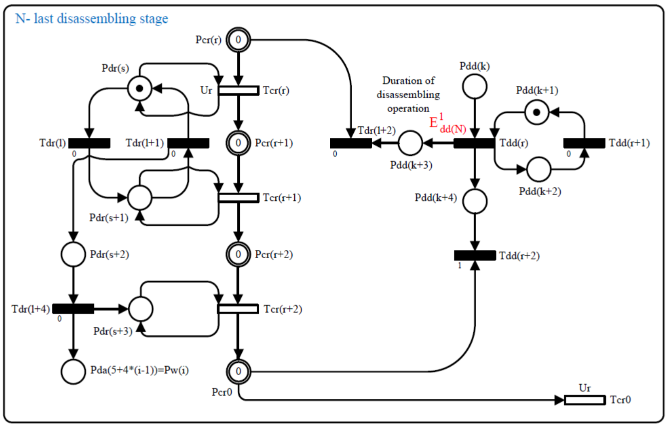

Figure 8. SHPN model of the last disassembly operation, $j=N$

- $D(W_{N+1-j}, N_{d_{j+1}})$ - the distance between the last storage warehouse W_{N+1-j} and the next disassembly location $N_{d_{j+1}}$.
- $D_{r_j}=D(N_{d_j}, W_{N+1-j})+D(W_{N+1-j}, N_{d_{j+1}})$ - the distance travelled by the mobile robot during stage j of disassembly.
- $r=1+(j-1)\cdot 3$ - the indexes of a continuous place associated the robot states (Pcr); a continuous transition of the robot (Tcr) and a discrete transition of disassembly process (Tdd).
- $k=1+(j-1)\cdot 5$ - the indexes of a discrete place within the disassembly process (Pdd).
- $l=1+(j-1)\cdot 4$ - the indexes of a discrete place of the robot states, Tdr .

III. THE FORMALISM OF SHPN MODEL

The SHPN model associated to A/DML is a triplet,

$$SHPN=\langle THPN, E, Sync\rangle, \tag{1}$$

such that: $THPN$ is a septuplet

$$THPN = \langle P, T, Pre, Post, m_0, h, tempo \rangle, \tag{2}$$

E is a set of external events

$$E = \left\{Edd_i^1, Edd_i^2\right\} \cup \{e\}, i = 1 + 3(k-1), j = 3(k-1), k = \overline{1,N}, \tag{3}$$

$Sync$ is a function from the set of the discrete disassembly transitions to the set of external events

$$Sync : T \rightarrow \left\{E^1, E^2\right\} \cup \{e\}, \tag{4}$$

where e is the constantly occurring event (the neutral element of the monoid E^*) and

$$Sync : \{Tdd_r\}_{r=1+3\cdot(k-1), k=\overline{1,N}} \rightarrow \left\{E^1, E^2\right\},$$

$$Sync : \{Tdd_i\}_{i=3\cdot(k-1), k=\overline{1,N}} \rightarrow \left\{Edd_i^2\right\}_{i=3\cdot(k-1), k=1,N},$$

$$Sync\!: T \setminus \{Tdd_r\}_{r=\overline{1,3+3(N-1)}} \cup \{Tdr_l\}_{l=\overline{1,4+5(N-1)}} \cup \{Tcr_r\}_{r=\overline{1,3+3(N-1)}} \rightarrow e,$$

$$P = \{P_1, P_2 \ldots P_n\} = P^D \cup P^C, \tag{5}$$

is a finite, not empty, set of places with P^D the set of discrete places

$$\begin{aligned} P^D = \{Pda_i\}_{i=\overline{1,13+4(N-1)}} \cup \{Pdd_r\}_{r=\overline{1,5+5(N-1)}} \\ \cup \{Pdr_s\}_{s=\overline{1,4+8(N-1)}} \end{aligned}, \tag{6}$$

and P^C the set of continuous places

$$P^C = \{Pcr_k\}_{k=\overline{0,3+3(N-1)}}, \tag{7}$$

where:

$\{Pda_i\}$ is the set of discrete places for the assembly process;

$\{Pdd_j\}$ is the set of discrete places for the disassembly process;

$\{Pdr_k\}$ is the set of discrete places for the mobile robot's states, while serving the disassembly process;

$\{Pcr_k\}$ is the set of continuous places associated withthe distances travelled by the mobile robot for each disassembly operation in order to transport the disassembled component from the disassembled location to the storage location;

$$T = \{T_1, T_2, \ldots, T_m\} = T^D \cup T^C, \tag{8}$$

is a finite, not empty, set of transitions with T^D as the set of discrete transitions

$$T^D = \{Tda_i\}_{i=\overline{1,7+2\cdot N}} \cup \{Tdd_r\}_{r=\overline{1,3+3\cdot(N-1)}} \cup \{Tdr_l\}_{l=\overline{1,4+5\cdot(N-1)}} \tag{9}$$

and T^C the set of continuous transitions

$$T^C = \{Tcr_r\}_{r=\overline{1,3+3\cdot(N-1)}},$$

where:

$\{Tda_i\}$ is the set of discrete transitions for the assembly operations model

$\{Tdd_j\}$ is the set of discrete transitions for the disassembly operations model;

$\{Tdr_k\}$ is the set of discrete transitions for the states of mobile robot while serving disassembly operations;

$\{Tcr_k\}$ is the set of continuous transitions associated to the distances travelled by the mobile robot for each disassembly operation. For these transitions the maximum linear speed of the WMR is attributed.

$Pre : P \times T \rightarrow Q_+$ or N is the input incidence application;

$Post : P \times T \rightarrow Q_+$ or N is the output incidence application;

$m_0 : P \rightarrow R_+$ or N is the initial marking;

$$h : P \cup T \rightarrow \{D, C\}, \tag{10}$$

called "hybrid function", indicates for every node whether it is a discrete node (sets P^D and T^D) or a continuous one (sets P^C and T^C),

$$h : P^D \cup T^D \rightarrow \{D\}; h : P^C \cup T^C \rightarrow \{C\}, \tag{12}$$

$tempo$ is a function from the set T of transitions to the set of positive or zero rational numbers,

$$tempo : T \rightarrow Q_+ \cup \{0\}. \tag{13}$$

If $T_j \in T^D$, $d_j = tempo(T_j)$ then this timing is associated with T_j. For each discrete assembly transition of the set

$$T_a^D = \{Tda_i\}_{i=2\cdot k, k=\overline{1,N}} \cup \left\{Tda_{2\cdot(N+1)}\right\}, \tag{14}$$

$$tempo(Tda_i) = d_{da_i}, \tag{15}$$

where d_{da_i} represents the duration (in seconds) associated to the corresponding assembly operation. For each discrete disassembly transition of the set

$$T_d^D = \{Tdd_r\}_{r=1+3\cdot(k-1), k=\overline{1,N}}, \tag{16}$$

d_{dd_r} is the duration of the corresponding disassembly operation. For each discrete WMR transition of the set

$$T_r^D = \{Tdr_l\}_{l=4+5\cdot(k-2), k=\overline{2,N}}, \tag{17}$$

d_{dr_l} is the duration of RM positioning in picking up and dropping for a disassembled component.

If $T_{cr} \in T^C$ then

$$U_r = \frac{1}{tempo(T_{cr})}, \qquad (18)$$

is the flow rate associated to T_{cr}.

For $T^C = \{Tcr_r\}_{r=3+3\cdot(k-1), k=\overline{1,N}}$, $U_{cr_r} = U_r; U_{r\max} = V_r$ where U_{cr} is the variable flow of the mobile robot displacement between disassembly stations. Consider the average speed of motion of WMR, $V_r = 94\, mm / s$.

Definition 1: The ED-enabling degree of a C-transition T_j for a marking m, denoted by $ED(T_j, m)$, is the enabling degree of T_j after all the arcs, from a C-place to a C-transition, have been removed:

$$ED(T_j, m) = \min_{P_i \in {}^0 T_j \cap P^D} \left(\frac{m_i}{Pre(P_i, T_j)} \right). \qquad (19)$$

Definition 2: The maximal firing speed of transition T_{cr_r} is the product of its flow rate U_r by its ED- enabling degree. Suitable definitions 1 and 2, for the general case, can be written as:

$$ED\left(T_{cr_j}, m_{cr(j+1)}\right) = \{0,1\}, \qquad (20)$$

$$m_{cr(j+1)} = V_j \cdot w\left(Tcr_j \times Pcr_{(j+1)}\right), \qquad (21)$$

$$w\left(Tcr_r \times Pcr_{r+1}\right) = D\left(W_{N+1-j}, N_{d_{j+1}}\right) / D\left(N_{d_j}, W_{N+1-j}\right), \qquad (22)$$

where $m_{cr(j+1)}$ is the mark associated to a continuous place and $w\left(Tcr_{(r)} \times Pcr_{(r+1)}\right)$ is the weight of the arc from a continuous transition to a continuous place of the WMR [9]. The analysis of SHPN model is relevant at a basic level in accordance with an elementary THPN module, denoted e-THPN. The SHPN model is obtained through the recurrent assembly of these elementary e-THPN modules (corresponding to each basic disassembly served by WMR with RM).

IV. SHPN MODEL CUSTOMISED FOR HERA & HORTSMANN MECHATRONIC LINE

For $N = 5$ the SHPN model becomes:

$$P^D = \{Pda_i\}_{i=\overline{1,29}} \cup \{Pdd_j\}_{j=\overline{1,25}} \cup \{Pdr_k\}_{k=\overline{1,41}},$$

$$P^C = \{Pcr_k\}_{k=\overline{0,15}},$$

$$T^D = \{Tda_i\}_{i=\overline{1,17}} \cup \{Tdd_j\}_{j=\overline{1,15}} \cup \{Tdr_k\}_{k=\overline{1,24}},$$

$$T^C = \{Tcr_k\}_{k=\overline{1,15}} \; T_a^D = \{Tda_i\}_{i=\{2,4,6,8,10\}} \cup \{Tda_{12}\},$$

$$tempo(Tda_i)_{i=\{2,4,6,8,10,12\}} = \{9.5, 9.3, 8.5, 0.5, 4.75, 27.2\},$$

where d_{da_i} represents the duration of the current assembly operation together with the transport time to the next assembly location, for $i \in \{2,4,6,8,10\}$, and the duration of the quality test together with the transport time to the elevator of the end storage warehouse, for $i \in \{12\}$;

$$T_d^D = \{Tdd_r\}_{r=\{1,4,7,10,13\}},$$

$$tempo(Tdd_r)_{r=\{1,4,7,10,13\}} = \left(d_{dd_r}\right)_{r=\{1,4,7,10,13\}} = 1,$$

$$T_r^D = \{Tdr_l\}_{l=\{4,9,14,19\}},$$

$$tempo\ (Tdr_l)_{l=\{4,9,14,19\}} = \left(d_{dr_l}\right)_{l=\{4,9,14,19\}},$$

$$\left(d_{dr_l}\right)_{l=\{4,9,14,19\}} = \{5.1, 21.2, 8.9, 7.8\},$$

$$Sync: \{Tdd_j\}_{j=\{1,3,4,6,7,9,12,13\}} \rightarrow \{Edd^1, Edd^2\}$$

where:

$$Sync: \{Tdd_i\}_{i=\{1,4,7,13\}} \rightarrow \{Edd_i^1\}_{i=\{1,4,7,13\}},$$

$$Sync: \{Tdd_i\}_{i=\{3,6,9,12\}} \rightarrow \{Edd_i^2\}_{i=\{3,6,9,12\}},$$

$$Sync: \{Tdd_j\}_{j=\overline{1,16}} \cup \{Tdr_k\}_{k=\overline{1,21}} \cup \{Tcr_k\}_{k=\overline{1,10}} \rightarrow e.$$

Consider the average speed of motion of WMR, $V_r = 94\, mm / s$. In Fig.9, the simulated response of the continuous place markings corresponding to $j = 1$ is shown as following: $Mcr(r)$ – the temporal variation of the travelled distance by the robot between stage 1 of disassembly and warehouse 5 (1031mm according to Fig.3); $Mcr(r+1), Mcr(r+2)$ – the variation of the distance to be travelled by the robot in the following stage (730mm according to Fig.3) correlated to the synchronization of the events Edd_1^1 and Edd_3^2.

V. OPTIMIZATION OF THE TIME CYCLE CORRESPONDING TO THE CONTROL OF REPETITIVE PROCESSES

Within the e_SHPN network, the weight of the arcs $w_r = \left(Tcr_r \times Pcr_r\right)\big|_{r=1+3\cdot(j-1)_{j=\overline{1,N}}}$ and $w_{r+1} = \left(Tcr_{r+1} \times Pcr_{r+1}\right)\big|_{r=1+3\cdot(j-1)_{j=\overline{1,N}}}$, for $r = 1 + 3\cdot(j-1)_{j=\overline{1,N}}$ are:

$$\begin{cases} w_r = D\left(W_{N+1-j}, N_{d_{j+1}}\right) / D\left(N_{d_j}, N_{N+1-j}\right) \\ w_{r+1} = D\left(N_{d_{j+1}}, W_{N-j}\right) / D\left(W_{N+1-j}, N_{d_{j+1}}\right) \end{cases}. \qquad (23)$$

The elementary time cycle (ETC) for the mobile robot (corresponding to the e_SHPN model, stage "j") is the travel duration with constant speed between storage warehouse-disassembling location added to the durations of disassembly and the manipulation operations performed by mobile robot: • the duration of the disassembly operation corresponding to “j” stage of disassembly (d_{dd_r}); • the travel duration: workstation for disassembling - storage warehouse $D\left(N_{d_j}, W_{N+1-j}\right) / Vr$

; storage warehouse – next disassembly workstation $D\left(W_{N+1-j}, N_{d_{j+1}}\right)/Vr$; • the picking-up and dropping durations of a disassembled component, followed by the gripper closure (d_{dr_l}) . The duration of the elementar cycle (T_{ECT}) for the mobile robot are:

$$\begin{aligned} T_{ETC} &= D\left(N_{d_j}, W_{N+1-j}\right)/V_r + d_{dd_j} \\ &\quad + d_{dr_{j+3}} + D\left(W_{N+1-j}, N_{d_{j+1}}\right)/V_r \Big|_{j=\overline{1,N}} \end{aligned} \tag{24}$$

Once these variables within the SHPN model are identified, this relationship becomes:

$$\begin{aligned} T_{ETC} &= \left(m_{cr_{r+1}}\right)/Vr = \left(m_{cr_r}\right)/Vr + d_{dd_j} \\ &\quad + d_{dr_{j+3}} + \left(m_{cr_{r+2}}\right)/V_r \Big|_{r=1+3\cdot(j-1), j=\overline{1,N}} \end{aligned} \tag{25}$$

where, for $r = 1 + 3\cdot(j-1)_{j=\overline{1,N}}$:

$$\begin{aligned} m_{cr_r} &= D\left(N_{d_j}, W_{N+1-j}\right) \\ m_{cr_{r+2}} &= m_{cr_r}\cdot w_r \cdot w_{r+1} = D\left(W_{N+1-j}, N_{d_{j+1}}\right) \end{aligned}$$

The optimization of the time cycle (TCO) for the mobile robot implies the minimization of the disassembly operations duration (if possible) and the minimization of manipulation durations. At the same time the temporal synchronization between ETC and the disassembly duration added to the travel time of the product between two successive workstations must be provided. Within the SHPN model this restriction is equivalent to the avoidance condition of PN model blockage:

$$\begin{cases} TCO = \sum_{j=1}^{N} D\left(N_{d_j}, W_{N+1-j}\right)/V_r \\ \qquad + \min\left(\sum_r d_{dd_r} + \sum_l d_{dr_l}\right)\Bigg|_{\substack{r=1+3\cdot(k-1), k=\overline{1,N} \\ l=4+5\cdot(k-2), k=\overline{2,N}}} \\ \qquad + \sum_{j=1}^{N} D\left(W_{N+1-j}, N_{d_{j+1}}\right)/V_r \\ \min\left(d_{dd_r} + d_{dr_l}\right) + D\left(W_{N+1-j}, N_{d_{j+1}}\right)/V_r \Big|_{\substack{r=1+3\cdot(k-1), k=\overline{1,N} \\ l=4+5\cdot(k-2), k=\overline{2,N}}} \\ \qquad \le d_{dd_r} + d_{dd_{r+1}} \Big|_{r=1+3\cdot(k-1), k=\overline{1,N}} \end{cases} \tag{26}$$

VI. CONCLUSIONS

In this paper, a THPN model in synchronized form, based on real-time control of fully reversible assembly/disassembly mechatronics line and in synchronized form is presented. The SHPN model is conditioned on certain state transitions by external events representing signals supplied by sensors. The A/DML is served by a WMR equipped with RM which is used only in the disassembling process in order to transport the disassembled components to the storage warehouses. Therefore, the assembly line becomes reversible, i.e. executes automated disassembly. A disassembly process is initiated when the final product, obtained through assembly, fails the quality test. The SHPN model has been tested via simulation and used in real-time control. The results obtained

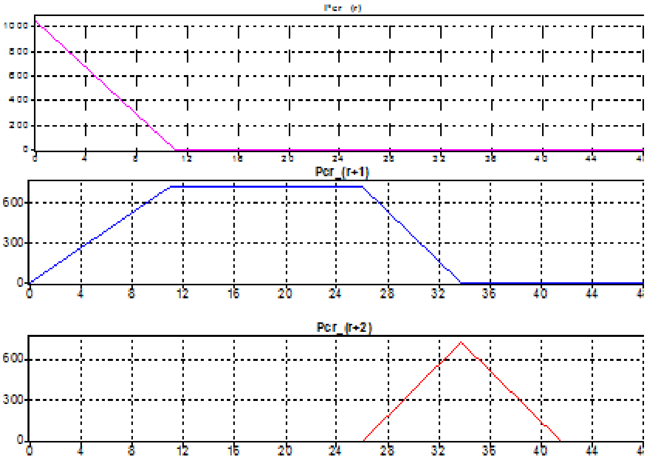

Figure 9. Variation of the continuous places asociated to displacements of WMR and RM corresponding to the j- stage of disassembling

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