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# Modeling and Control of Assembly/Disassembly Mechatronic Line Served by Robotic Manipulator Mounted on Mobile Platform

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**Abstract:** The new idea of this paper is to make reversible an assembly mechatronic line, *i.e.* to allow complete disassembly, by using a mobile platform equipped with robotic manipulator. The approach is a hybrid one, in which the assembly/disassembly line is the discrete system while the wheeled mobile robot (WMR) together with the robotic manipulator (RM) is considered the continuous one. The mobile platform is used only in disassembling operations, in order to transport the components from the disassembling locations to the storage locations. Therefore, Synchronized Hybrid Petri Nets (SHPN) approach is used in modeling and control. This hybrid system takes into consideration the distribution of the necessary tasks to perform the hybrid disassembly of the components, using robot synchronization with flexible line process. The ultimate goal is to make completely reversible the assembly line. The SHPN model is transposed into LabView platform, such as to get a control structure of the mechatronic line and of WMR.

*Keywords:* Hybrid Petri Nets; robotic manipulators; flexible manufacturing systems; mobile robots.

## 1. INTRODUCTION

The main contribution of paper consists in control of a mechatronic assembly/disassembly flexible manufacturing system (FMS) served by a WMR equipped with RM based on a SHPN model in connection with sliding-mode control of the mobile platform. The SHPN model was initially devoted to modelling cyclic process of assembling and disassembling (Radaschin et al. 2011). Actually, the SHPN model, implemented into LabVIEW platform, becomes a real-time control of the hybrid system, FMS and RM mounted on WMR. The novelty of the research is the SHPN model corresponding to FMS served by WMR equipped with RM, which, for the first time, describes the dynamics of the continuous system by using Timed Hybrid Petri Nets (THPN). This approach is completely different of the others. The continuous feature is associated to the WMR displacement, WMR equipped with RM being the assistance system, during disassembling process, at the workplaces of the FMS. This model gives a high-level description of the product to be disassembled. Also, the continuous subsystem, integrated into a hybrid system, in connection with synchronization signals, confers implementation potential of the SHPN model into a real-time control platform.

This paper is organized as follows: system description is presented in Section 2; in Section 3, the disassembly task scheduling is presented; the description of the SHPN model together with external events are presented in Section 4; Section 5 is reserved to monitoring and control of assembly and disassembly process by LabVIEW interface together with the closed loop control of the WMR equipped with RM; some conclusions and future research direction are presented in Section 6.

## II. MECHATRONIC LINE DESCRIPTION

Since the assembly line HERA (Fig. 1), does not initially implement fully automatic disassembly, this paper presents an extension of the control system in order to perform complete disassembly. Therefore, the system designed initially to perform automatic assembling, becomes here a reversible one, by the implementation of a hybrid control system for automatic disassembling, served by a mobile platform equipped with manipulator. The robot has its own odometric system. An on-board embedded microcontroller is able to read the position information, to send it over a radio communication link according to a specific protocol and to send the data to the PLC of the manufacturing flexible line. The WMR is equipped with RM having three articulations and one gripper paddles. The assembly/disassembly manufacturing flexible line is equipped with SIEMENS Simatic S7-300 PLC (Programmable Logic Controller), with 5 distributed modules connected by Profibus DP network for every station. The flexible line includes: five individual workstations with different tasks (carrying and transporting), pneumatic workstations, conveyor belt, sorting unit, test station and warehouse. The work part carrier is used for

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Fig. 1. Assembly line, Hera, served by WMR, Pioneer 3-DX, equipped with RM, Pioneer 5-DOF Arm
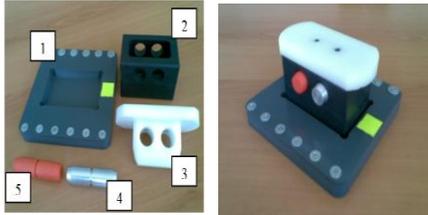


Fig. 2. a) components; b) assembled product.

carrying and transporting the four-piece work part on the conveyor belt system. The work part carrier is equipped with 6-Bit identification which provides large number of possible codes, read out by inductive sensors. The four-piece work part enable workflow model such as assembling, testing, sorting, storage and disassembling. The components to be assembled are (Fig. 2): work part carrier (base platform) (1), body (2), cover (3), metal cylinder (4) and plastic cylinder (5). For the disassembly operation, the configuration of the product's components is needed. This includes position and orientation of components and the material it is made (plastic or metal), elements that are relevant for the activation of the hybrid disassembly operation.

## III. DISASSEMBLY BY USING WMR EQUIPPED WITH RM AND TASK PLANNING

A robotic disassembly system consists of many different kind of component such as mobile robot, flexible line, sensors, handling and transport mechanisms. The disassembly operation can be decomposed into a sequence of elementary tasks coupled in parallel with movements of the robot pick-up/dropping /positioning. The assembly operation can by decomposed into a sequence of elementary assembly tasks coupled in parallel with positioning tasks of work-piece along conveyor, (Baldwin et al. 1991, Choi et al. 1998, Rosell, 2002 and Ganget et al., 2005). The hybrid disassembly strategy is based on the hierarchical model (Seliger et al. 1999, Radaschin et al. 2011, Radaschin et al.2012, Kopacek B. and Kopacek P. 2010), which uses a graph representation of the product, where the relations among components are expressed by means of arrows. If the fully assembled product does not pass the quality test, the task planner provides the best sequence to completely disassemble the product, such as shown in Fig. 3 and Fig. 4.
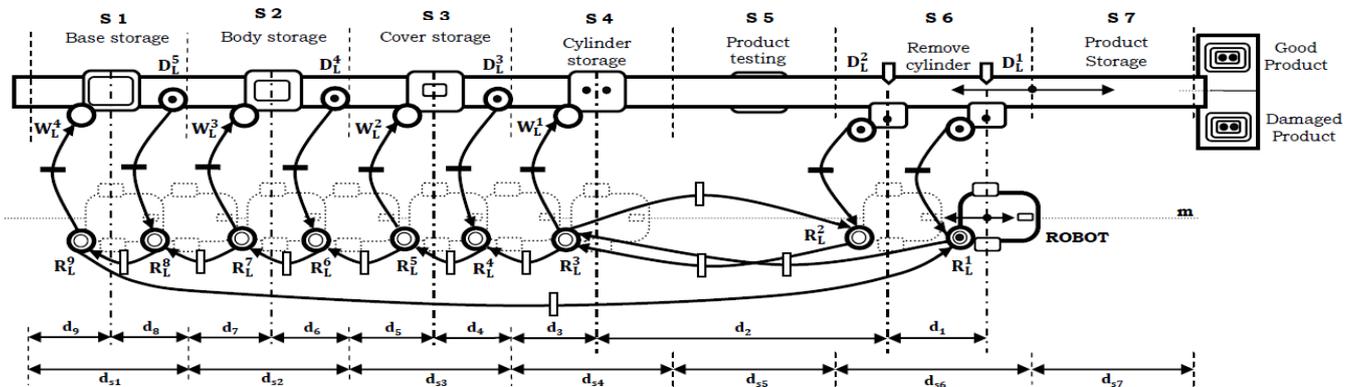


Fig. 3. Disassembly operations and component transportation to the storage warehouses by WMR equipped with RM

## IV. MODELING BY SYNCHRONIZED HYBRID PETRI NETS

The system of reversible assembly/disassembly line served during the disassembling process by robotic manipulator mounted on mobile platform, (whose schematic is shown in Fig. 3) has a dynamics determined by events (supplied by the control sequences of the automatic system), which represent the discrete event component of the system and by the interaction with the WMR, which represents the continuous time component of the system. The considered system is a hybrid one and requires specialized tools for modelling, (Rosell,2002). The hybrid model is elaborated using a HPN modeling tool, (David and Alla, 2010). Combining the SED model of the analyzed system with the cyclic and continuous time of the robotic manipulator mounted on mobile platform, results in a synchronized hybrid model, SHPN. The SHPN structures (Fig. 4 and Fig.5) and the SHPN model (Fig. 7) are obtained by modelling assembly/disassembly sequences and use continuous assistance service for disassembly operations performed by mobile platform equipped with manipulator. SHPN morphology results by integration of three PN models. Each of these models has a specific typology: TPN (Timed PN), SPN (Syncronised PN) and THPN (Timed Hybrid PN). These models describe the following automatic operations:

- Assembly/storage in warehouses (TPN typology);

- Disassembly of damaged product (SPN and TPN typologies);

- Service assistance during disassembling process performed by the mobile robot equipped with manipulator (THPN typology).
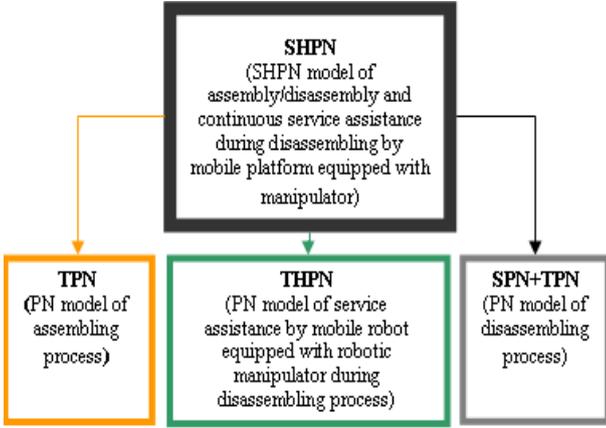


Fig. 4. SHPN decomposition in subsystems: assembling, WMR equipped with RM and disassembling

The SHPN model associated to the assembly/disassembly, (Fig. 12) is a triplet:

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

such that: $THPN$ is a seventhly

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

$E$ is a set of external events

$$E = \left\{ E_i^1, E_j^2 \right\}_{\substack{i \in \{1,4,7,10,13\} \\ j \in \{3,6,9,12,15\}}} \cup \{e\} \tag{3}$$

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

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

where $e$ is the always an occurring event (it is the neutral element of the monoid $E^*$).

It follows a detailed explanation for each component of SHPN model from (1):

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

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

$$P^D = \{Pda_i\}_{i=\overline{1,22}} \cup \{Pdd_j\}_{j=\overline{1,26}} \cup \{Pdr_k\}_{k=\overline{1,16}} \tag{6}$$

and $P^C$ the set of continuous places

$$P^C = \{Pcr_k\}_{k=\overline{1,15}} \tag{7}$$

$\{Pda_i\}_{i=\overline{1,22}}$ is the set of discrete places for assembly process;

$\{Pdd_j\}_{j=\overline{1,26}}$ is the set of discrete places for disassembly process;

$\{Pdr_k\}_{k=\overline{1,16}}$ is the set of discrete places for the states of mobile robot while serving disassembly process;

$\{Pcr_k\}_{k=\overline{1,15}}$ is the set of continuous places associated to the distances performing by the mobile robot for each disassembly operation in order to transport the disassembled component from the disassembled location to the storage location;

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

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

$$T^D = \{Tda_i\}_{i=\overline{1,14}} \cup \{Tdd_j\}_{j=\overline{1,16}} \cup \{Tdr_k\}_{k=\overline{1,21}} \tag{9}$$

and $T^C$ the set of continuous transitions

$$T^C = \{Tcr_k\}_{k=1,10} \tag{10}$$

$\{Tda_i\}_{i=\overline{1,14}}$ is the discrete transitions for assembly operations;

$\{Tdd_j\}_{j=\overline{1,16}}$ is the set of discrete transitions for disassembly operations model;

$\{Tdr_k\}_{k=\overline{1,21}}$ is the set of discrete transitions for states of mobile robot while serving disassembly operations;

$\{Tcr_k\}_{k=1,10}$ is the set of continuous transitions associated of distances performing by the mobile robot for each disassembly operation. To these transitions is associated the maximum linear speed of the WMR.

The sets $P$ and $T$ are disjointed $P \cap T = \varnothing$;

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

$$h : P \cup T \rightarrow \{D, C\}, \tag{11}$$

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 $T^C$).

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

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

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

Remark 1: In the definitions of $Pre$, $Post$ and $m_0$, $N$ corresponds to the case where $P_i \in P^D$, and $Q_+$ or $R_+$ corresponds to the case where $P_i \in P^C$;

$tempo$ 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 $T_j \in T^D$, then $d_j = tempo(T_j)$ is timing associated with $T_j$.

For $T^D = \{Tda_i\}_{i=\overline{1,14}}$, then $d_{da_i} = 1$ where $d_{da_i}$ represents the delay associated to the corresponding assembling operation.

For $T^D = \{Tdd_j\}_{j=\overline{1,16}}$, then $d_{dd_j} = 1$, where $d_{dd_j}$ represents the transportation delay between disassembling location.

For $T^D = \{Tdr_k\}_{k=\overline{1,21}}$, then $d_{dr_k} = \{0,1\}$ where $d_{dr_k}$ represents picking up and dropping down delays of WMR equipped with RM in front of disassembling or storage locations.

If $T_j \in T^C$, then $U_j = \dfrac{1}{tempo(T_j)}$ is the flow rate associated to $T_j$.

For $T^C = \{Tcr_k\}_{k=\overline{1,10}}$, then

$$U_{cr_k} = \{\{v_k\}_{k=i+4} \cup \{v_k\}_{k=i}\}_{i=\overline{1,6}} \qquad (14)$$

where $U_{cr}$ represents the variable flow of mobile robot displacement between disassembly stations.

*Definition 1*: The maximal firing speed of transition $T_j$ is the product of its flow rate $U_j$ by its D-enabling degree

$$V_j = U_j \cdot D(T_j, m) \qquad (15)$$

*Definition 2*: The D-enabling degree of a C-transition $T_j$ for a marking m, denoted by, is the enabling degree of $T_j$ after all the arcs from a C-place to a C-transition have been deleted:

$$D(T_j, m) = \min_{P_i \in {}^0 T_j \cap P^D} \left\lfloor \frac{m_i}{Pre(P_i, T_j)} \right\rfloor \qquad (16)$$

Particularly, to the present SHPN, the arches $(P_i \times T_j)$, where $P_i = \{ROBOT\ state1, ROBOT\ state2\} \in {}^o \{Tcr_k\}_{k=\overline{1,10}} \cap P^D$, have the weight equal to one. Therefore, $Vcr_k = Ucr_k = 2|_{k=\overline{1,10}}$

$\{E_i^1\}\ i \in \{1,4,7,10,13\}$ is the set of external synchronization signals, supplied by the sensors, corresponding to STOP line and START disassembling;

$\{E_j^2\}\ j \in \{3,6,9,12,15\}$ is the set of external synchronization signals, supplied by the sensors, corresponding to PICKING UP of disassembled component and START line;

*Remark 2*: for a synchronized PN a transition is enabled when each of its input places contains enough tokens. If it is enabled, it is firable on occurrence of the event associated with it.

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

$$Sync : T \rightarrow \{E^1, E^2\} \cup \{e\} \qquad (17)$$

and can be expressed as follow:

$$Sync : \{Tdd_j\}_{j=\overline{1,16}} \rightarrow \{E^1, E^2\} \qquad (18)$$

where:

$$Sync : \{Tdd_i\}_{i=\{1,4,7,13\}} \rightarrow \{E_i^1\}_{i=\{1,4,7,13\}} \qquad (19)$$

$$Sync : \{Tdd_i\}_{i=\{3,6,9,12,15\}} \rightarrow \{E_i^2\}_{i=\{3,6,9,12,15\}} \qquad (20)$$

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

The hybrid aspect of the $SHPN$ model is determined by the variables associated to distances. These distances are travelled by the mobile platform between disassembling locations. $\{D_L^i\}_{i=\overline{1,5}}$ represent disassembling locations, $\{D_L^1, D_L^2\}$ for cylinders and $\{D_L^3, D_L^4, D_L^5\}$ for cover, body and base, respectively (Fig. 3). The variation of these variables is with constant or variable speed. These variations represented the mobile platforme speed between $\{D_L^i\}_{i=\overline{1,5}}$ points of mecatronic line.

The analysis of the SHPN model is relevant at the basic level accordingly with an elementary THPN module, denoted e-THPN (Fig.6). SHPN model is obtained by recurrent assembling of these elementary e-THPN modules. The SHPN global model is an exclusive relationship between TPN associated to the assembling process, elementary THPN modules associated to WMR service assistance and SPN with TPN associated to disassembling process.
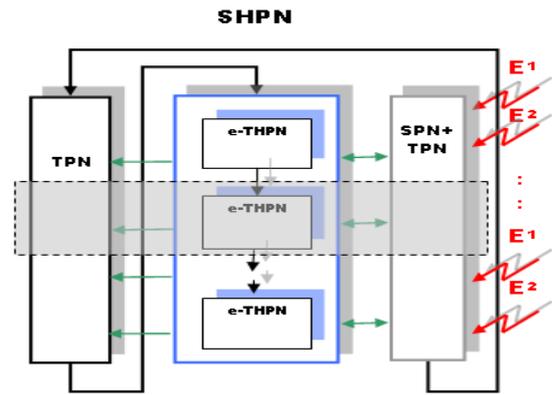


Fig.5. SHPN representation by structural blocks with elementary THPN modules (e-THPN).

## 5. REAL-TIME CONTROL OF REVERSIBLE MECHATRONIC MAUFACTURING LINE

The HPN model is transposed under LabVIEW platform in a real-time application (Fig.10). The real-time application is

obtained by interfacing HPN model with synchronized signals obtained by acquisition on the real process. At the conceptual level, the control platform corresponds to a synchronized HPN model (SHPN). The synchronization of real-time application with the controlled process is achieved by the positioning signals of the work piece along the conveyor, obtained by the acquisition board NI USB-6008. The synchronization signals, used in the LabVIEW application of real-time control, validate certain transitions into SHPN model. These transitions are conditioned by the associated signals of the position work piece on the conveyor track. The synchronization will lead to initialize robot and to monitoring/control operations of assembly/disassembly of WMR served with RM. In this way both the robot and flexible line are controlled, in order to achieve a minimal time cycle of assembly/disassembly. The initialization of the robot is performed by a signal transmitted through a wireless access point mounted on the robot, received by the LabVIEW application. Through the acquisition board, the state signals are transmitted to the flexible line in order to control position of the work piece along with the conveyor and for robot synchronization with the flexible line. The signal transmitted by the acquisition board to SIMATIC S7-300 PLC of the flexible line is done by the I/O module of LabView.



Fig. 6. State transition of disassembly components and their transportation to the storage location

Discrete-time sliding-mode control for trajectory-tracking, based on a kinematic model is used in order to control WMR Pioneer 3-DX. Pioneer 3-DX is a mobile platform with two driving wheels and one rear wheel. The robotic manipulator, Pioneer 5-DOF Arm, mounted on mobile platform, is controlled in open loop by step by step motors located in each joint. The gripper positioning in order to grab the disassembled component and its storage in the warehouse has been made by a visual servoing system. The state transition of disassembly components and of the WMR for transporting them to the storage location are shown in Fig.11.

## 6. CONCLUSION

A SHPN model for the control of a fully reversible assembly/disassembly manufacturing line is presented in this paper. The SHPN model is conditioned by certain state transitions with external signals from sensors. In order to perform disassembly, a robotic manipulator mounted on a mobile platform is used. Therefore, the assembly line becomes reversible, *i.e.* executes automated disassembly. A disassembling process is started when the final product, (obtained by assembling), is damaged. The disassembled components are recovered and transported to storage locations, in order to be used again in assembly process. As a future research direction, different mobile robots equipped with robotic manipulator should be used in order to transport small, medium and heavy weights disassembled components.

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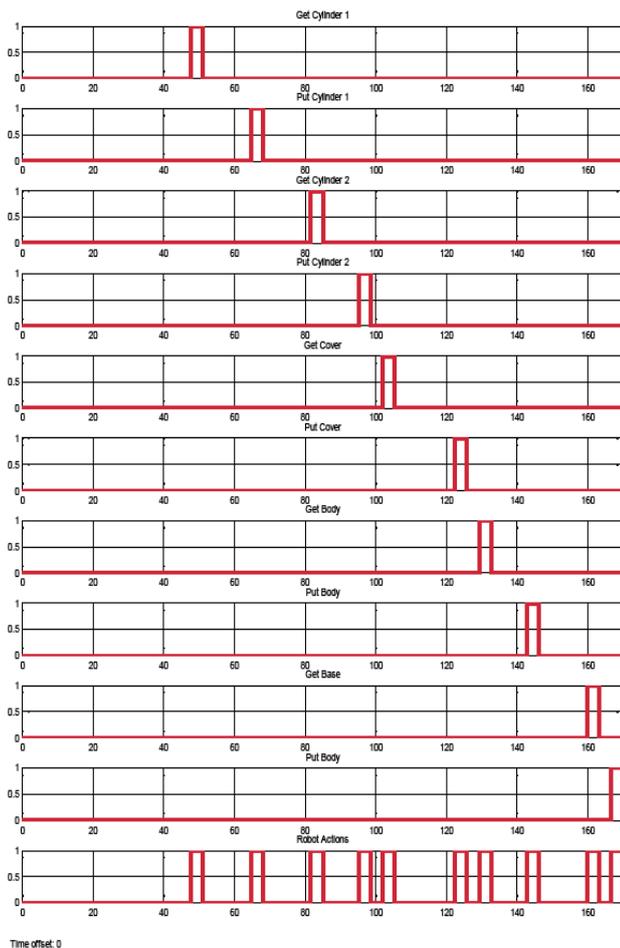
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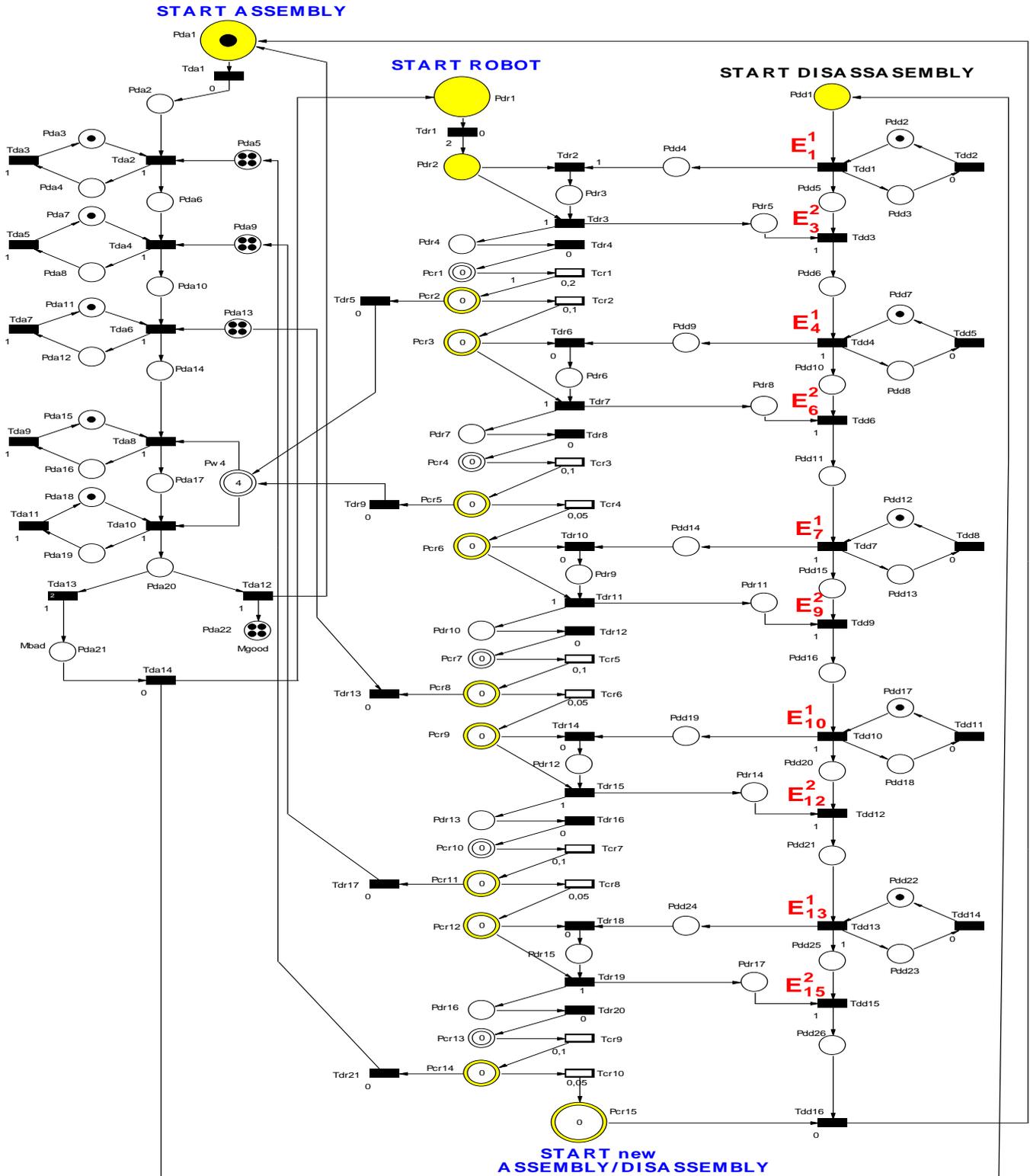
Fig. 7. SHPN model, in hybrid approach, of assembly/disassembly line served by WMR equipped with RM