Cycle Time Optimization of a Reversible A/DML Served by a Mobile Robotic System

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***Abstract*— This paper presents a new cycle time optimization (CTO) approach for an assembly/disassembly mechatronics line (A/DML) served by a wheeled mobile robot (WMR) equipped with a robotic manipulator (RM). The mobile robot serves A/DML during disassembling for transporting carry the disassembled components from disassembling locations to the corresponding storage warehouse in order to be reused. Disassembling starts if the final product fails the quality test. The cycle time results from adding up the durations of A/D sequences. Since the elementary assembly operations have constant durations (determined by the duration of the each assembly operation and the displacement duration of transporting line at constant speed, between successive workstations), the problem of cycle time optimization concerns only disassembling. During the disassembly, a repetitive sequence can be identified with a single disassembling stage served by WMR equipped with RM. In this case, an elementary cycle time (ECT) optimization is the maximum value between the following time durations: a) time duration of disassembling and transporting remaining piece towards next station; b) time duration of the RM for gripping and storage disassembled part and WMR's displacement. For the events synchronization are inserted the time intervals between: the displacement with constant speed within/between work stations and the manipulations/displacements of the robotic system. For setting time durations and joining the discrete dynamics of the mechatronics line with the continuous dynamics of the robotic system, a Synchronized Hybrid Petri Nets (SHPN) model running autonomously has been used.**

Keywords*— *cycle time; mechatronics line; mobile robots; hybrid mode; Petri Nets.

I. Introduction

The manufacturing systems for assembly/disassembly operations are complex control systems witch require a special approach and conditions of succcesive, parallel or synchronized tasks. In this respect, it is imporant for A/DML systems the hybrid systems approach because these have the hybrid system characteristics. The A/DML system dynamics consisting of continuous dynamic behaviors and discrete event behaviors. For A/DML modeling the Hybrid Petri Nets (*HPNs*) tools are used ([6], [10]).

The pieces obtained by assembly/disassembly consist of parts or subassemblies that are successively mounted ([1]). The most relevant topics include the research about assembly / disassembly operations, tasks planning, manufacturing lines balancing, sequence planning, etc. A comprehensive based on knowledge approach to disassembly task planning is required. In this sense which considers all aspects of interaction and domain knowledge subjected to economic and technical constraints. The knowledge development based on a HPN model which integrated a sequential algorithm was successfully applied to modeling of a flexible disassembly process and and planning of a repetitive tasks.

For all that, the autonomous mobile robot typology, the disassembly and task level planning, improves the efficiency of the disassembly process and reduces the cost of product. In low-level task planning it is proposed changing models or sequencing operations ([8]).

The dinamics of an Assembly/Disassembly Mechatronics Line (A/DML) served by a Wheeled Mobile Robot (WMR) equipped with a Robotic Manipulator (RM) is describe by the Synchronized Hybrid Petri Nets (SHPN). The critical issues are • the minimizing of valuable resources (time and money) that are invested in disassembly operations; • maximizing the automation level of disassembly process; • maximizing the quality of the components or materials recovered ([9]).

The SHPN model corresponding of assembly/disassembly tasks, describe both aspects: the discrete approach for the elementary A/D operations and the continuous approach for displacement of WMR. The considered system – A/DML is a hybrid one and requires specialized tools for modeling [4].

The hybrid model is elaborated using the dedicated PN tool – HPN which integrates the hybrid aspect modeling tool HPN [11], [5]. The SHPN model is used in the optimization of process parameters. The duration of cycle time for entire disassembly operations, requires the intervention in the strategy of mobile platform control.

This paper is organized as follows: the description of A/DML served by WMR with RM and SHPN model and the generalized SHPN formalism is presented in Section 2. Section

3 is reserved to the generalized approach of cycle time optimization for disassembling operations.

II. SHPN MODEL FOR A/DML SERVED BY WMR

The reversible A/DML served by robotic manipulators mounted on mobile platforms has a dynamics which can be described by the events occurrence. At the same time, the dynamics of this process is determined and by the interaction with the WMR- the continuous time component of the system.

The disassembly operation can by decomposed into a sequence of elementary disassembly tasks coupled in parallel with positioning tasks of work-piece along conveyor [2], [3]. The hybrid model for an assembly/disassembly proces is based on the hierarchical model [12] which uses the general representation from Fig. 1.

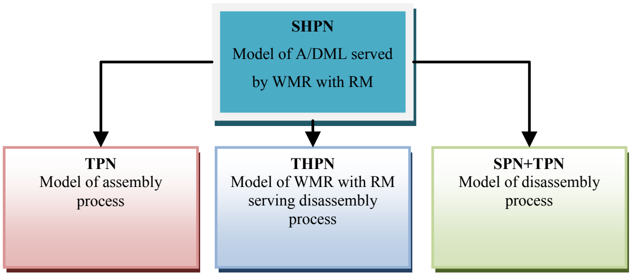


Fig. 1. Structure of SHPN model.

The hierarchical structure of SHPN structure from Fig. 1 is obtained by modeling of assembly/disassembly operations and continuous service assistance, for disassembly operations, performed by mobile platform equipped with manipulator: Assembling/storage in warehouses (TPN typology: Fig.1, Fig.2); Disassembling of damaged product (SPN and TPN typologies: Fig.1); Service assistance, during disassembling process, performed by the mobile robot (THPN typology: Fig.1).

The entire model is SHPN type includes synchronization concept because it is interfaced with external events for synchronization in an modeling/simulation approach, useful in real-time control. SHPN morphology results by integration three PN typoligie models. During disassembly process can identify a repetitive sequence associated to a single disassembly operation and service assistance of mobile robot. All of these can be modeled with a Elementary SHPN as is represented in Fig. 3.

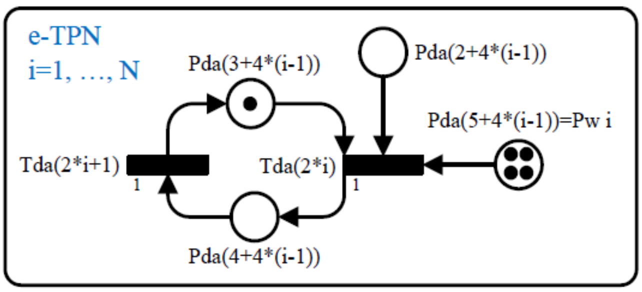


Fig. 2. e-TPN model for an elementary assembly operation

$E^1_{dd(j)}$ and $E^2_{dd(j+2)}$ are external events sent by the sensors used for line synchronization with the WMR. $E^1_{dd(j)}$ is an external synchronization signal, corresponding to STOPPING / STARTING line. $E^2_{dd(j+2)}$ is an external synchronization signals, corresponding to PICKING UP of disassembled component and STARTING line. All of these repetitive sequences can be modeled with a SHPN, called elementary SHPN (Fig. 2).

It is proposed the following notations (Fig.5):

- $N_{a_i}, i = \overline{1, N}$ - elementary assembly locations (on the positive sense of Ox axis)
- $N_{d_j}, j = \overline{1, N}$ - elementary disassembly locations (on the inverse sense of Ox axis)
- $W_i,\ i = \overline{1, N}$; where: $W_{N+1-j} \equiv W_i, j = \overline{1, N}$ - elementary warehouse locations (identically with the assembly locations)
- $D(W_{N+1-j}, N_{d_{j+1}})$ - distance between last storage warehouse W_{N+1-j} and the next disassembly location $N_{d_{j+1}}$.
- $D(N_{d_j}, W_{N+1-j})$ - distance between disassembly location N_{d_j} and the corresponding storage warehouse W_{N+1-j}
- $D_{r_j} = D(N_{d_j}, W_{N+1-j}) + D(W_{N+1-j}, N_{d_{j+1}})$ - distance travelled by the mobile robot in the j stage of disassembly. The generalized approach has been tested for an assembly/disassembly mechatronics line HERA&Horstmann [11].

A. *The SHPN Model Formalism*

The SHPN model corresponding to A/DML is a n-uplet

$$SHPN = \langle P, T, Pre, Post, m_0, h, tempo, E, Sync \rangle \tag{1}$$

E represent the set of external events

$$E = \left\{ Edd^1_i, Edd^2_j \right\}_{\substack{i=1+3\cdot(k-1) \\ j=3\cdot(k-1)}}\Big|_{k=\overline{1,N}} \cup \{e\} \tag{2}$$

$Sync$ represent a function defined by the set of the discrete disassembly transitions to the set of external events

$$Sync : T \to \left\{ E^1, E^2 \right\} \cup \{e\} \tag{3}$$

where e represent the always occurring event (the neutral element of the monoid E^*)

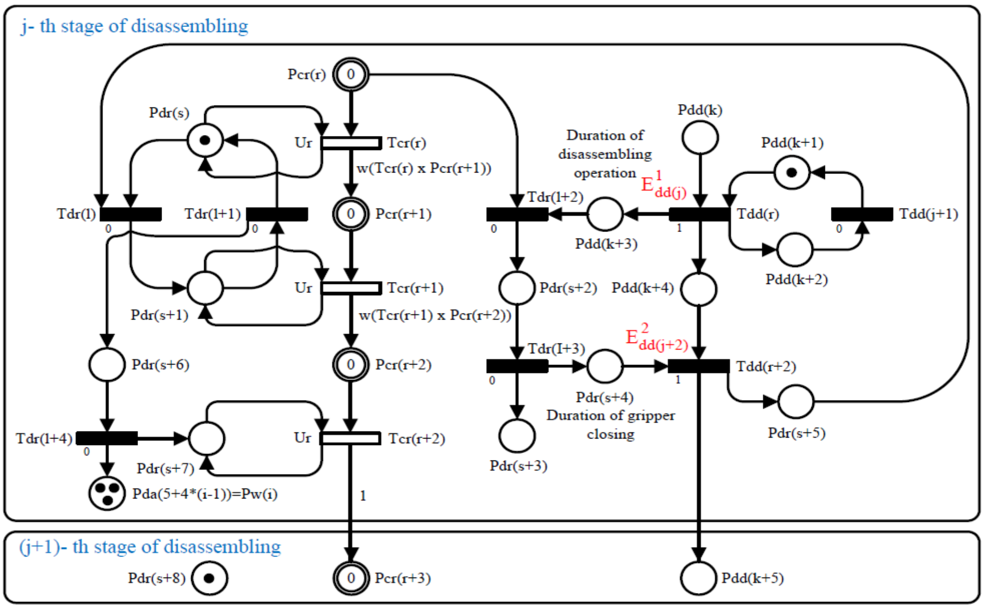


Fig. 3. e-SHPN model corresponding of j-th elementary disassembly operation

Fig. 4. A/DML of a 5-part product, served by the WMR

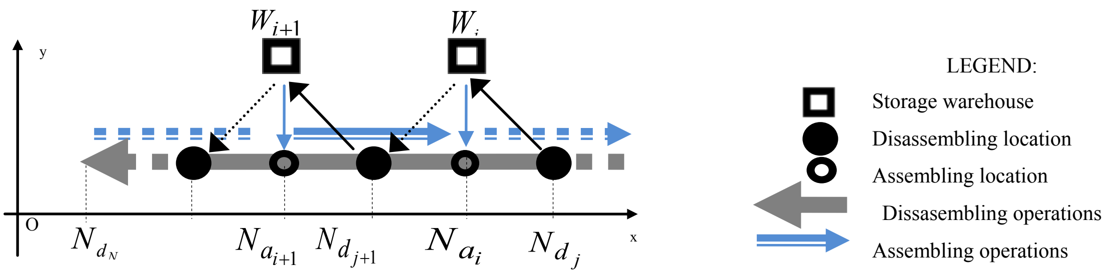


Fig. 5. Assembly/Disassembly and storage warehouse locations

$$Sync:\{Tdd_r\}_{r=1+3\cdot(k-1)_{k=\overline{1,N}}} \rightarrow \{E^1, E^2\} \tag{4}$$

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

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

where :

P^D represent the set of discrete places

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

P^C represent the set of continuous places

$$P^C=\{Pcr_k\}_{k=\overline{0,3+3(N-1)}} \tag{6}$$

where:

$\{Pda_i\}$ represent the set of discrete assembly places;

$\{Pdd_j\}$ represent the set of discrete disassembly places;

$\{Pcr_k\}$ represent the set of continuous places associated to the distances performing by WMR for each disassembly operation. The WMR transport the disassembled component from the disassembled location to the storage location;

$$T=\{T_1, T_2, \ldots, T_m\}=T^D \cup T^C \tag{7}$$

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

$$T^D = \{Tda_i\}_{i=\overline{1,7+2\cdot N}} \cup \{Tdd_r\}_{r=\overline{1,3+3\cdot(N-1)}} \cup \{Tdr_l\}_{l=\overline{1,4+5\cdot(N-1)}} \tag{8}$$

and T^C represent the set of continuous transitions

$$T^C = \{Tcr_r\}_{r=\overline{1,3+3\cdot(N-1)}} \tag{9}$$

where:

$\{Tda_i\}$ represent the set of discrete transitions for assembly operations; $\{Tdd_j\}$ represent the set of discrete transitions for disassembly operations; $\{Tdr_k\}$ is the set of discrete transitions for states of mobile robot while serving disassembly operations; $\{Tcr_k\}$ is the set of continuous transitions associated to distances performing by the mobile robot for each disassembly operation. To these transitions is associated the maximum linear speed of the WMR.

$$Pre : P \times T \rightarrow Q_+ \text{ or } N \tag{10}$$

is the input incidence application;

$$Post : P \times T \rightarrow Q_+ \text{ or } N \tag{11}$$

is the output incidence application;

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

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

$$tempo : T \rightarrow Q_+ \cup \{0\} \tag{12}$$

If $T_j \in T^D$, then $d_j = tempo(T_j)$ is timing associated with T_j. For each discrete assembly transition T, on defined: d_{da_i} is the duration of each disassembly actions; d_{dd_r} is the duration of the corresponding disassembly operation. d_{dr_l} is the duration of RM positioning in picking up and dropping down for a disassembled component.

III. Generalised Approach to Cycle Time Optimization for Disassembling Operations

The elementary cycle time (ECT) for the mobile robot ETC_R, corresponding to the elementary_SHPN model (e_SHPN) for stage j, is the displacement duration between N_{d_j} - the disassembling location, W_i - the storage warehouse, $N_{d_{j+1}}$ - the next disassembling location added to durations of disassembly and manipulation operations performed by mobile robot (Fig.5).

A. ECT in mobile robot cycle time approach

$$T_{travel\_r(j)} = T_{travel\_r(j,i)} + T_{travel\_r(i,j+1)}$$

where: $T_{travel\_r(j,i)}$ is the travel duration between N_{d_j} - the disassembling location to W_i - the storage warehouse; $T_{travel\_r(i,j+1)}$ is the travel duration between W_i - the storage warehouse to $N_{d_{j+1}}$ - the next disassembling location.

$$T_{travel\_r(j)} = D(N_{d_j}, W_{N+1-j})/v_r + D(W_{N+1-j} + N_{d_{j+1}})/v_r$$

where v_r is the linear speed of mobile robot on trajectories without obstacles. From N_{d_j} station the mobile robot starts moving towards the storage warehouse after the following sequences are completed: the pick-up of disassembled components and the gripper closure. In e_SHPN this durations corresponds of timing associated with continuous transitions T^C [11] (Fig. 3):

$$T_{travel\_r(j,i)} = tempo(Tcr_r)\Big|_{r=3+3\cdot(j-1)} \tag{13}$$

The durations of picking-up and dropping-down the disassembled components corresponds of manipulation actions for the j stage. In e_SHPN this durations corresponds of timing associated with discrete transitions T^D:

$$\begin{cases} T_{pick-up\_r_j} = d_{dr_{l+2}}\Big|_{\substack{l=1+(j-1)\cdot 4 \\ j=\overline{1,N}}} \\ d_{dr_{l+2}}\Big|_{\substack{l=1+(j-1)\cdot 4 \\ j=\overline{1,N}}} = d_{dr_{3+(j-1)\cdot 4}}\Big|_{j=\overline{1,N}} \end{cases} \tag{14}$$

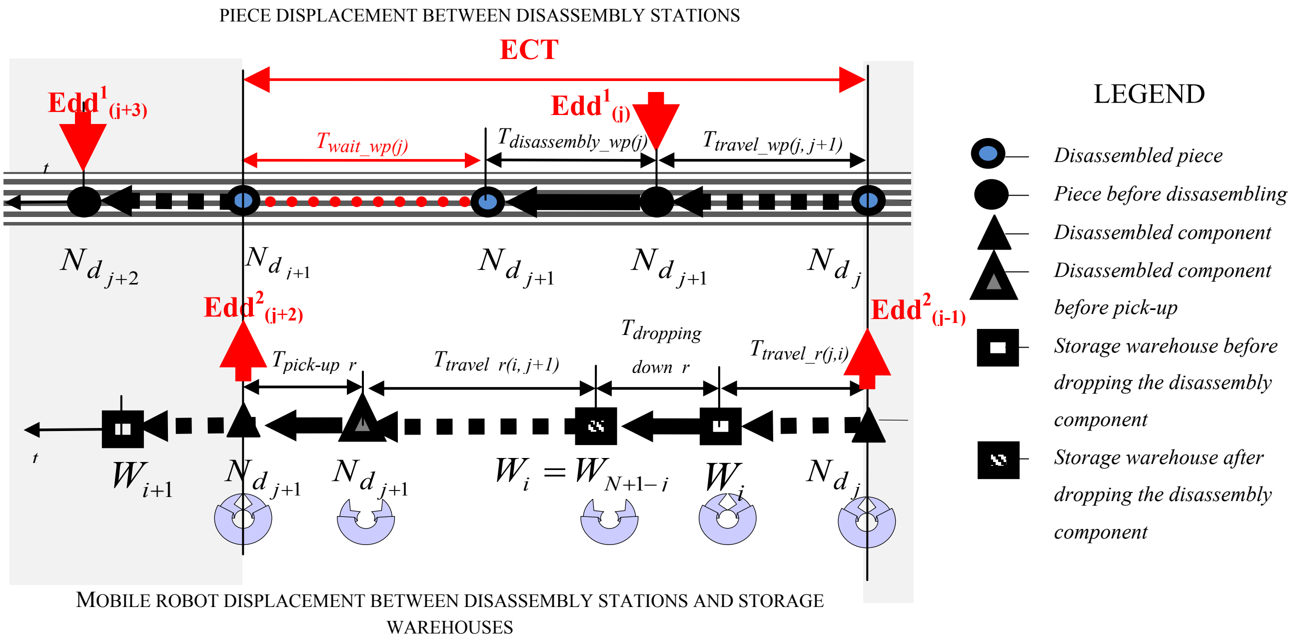
$$\begin{cases} T_{dropping\_down\_r_j} = d_{dr_{l+3}}\Big|_{\substack{l=1+(j-1)\cdot 4 \\ j=\overline{1,N}}} \\ d_{dr_{l+3}}\Big|_{\substack{l=1+(j-1)\cdot 4 \\ j=\overline{1,N}}} = d_{dr_{4+(j-1)\cdot 4}}\Big|_{j=\overline{1,N}} \end{cases} \tag{15}$$

The duration of cycle time and its components can be identified within the temporal marking evolution corresponding to j stage of SHPN model. In this case the ECT for the mobile robot approach- ETC_R corresponding to j stage, are:

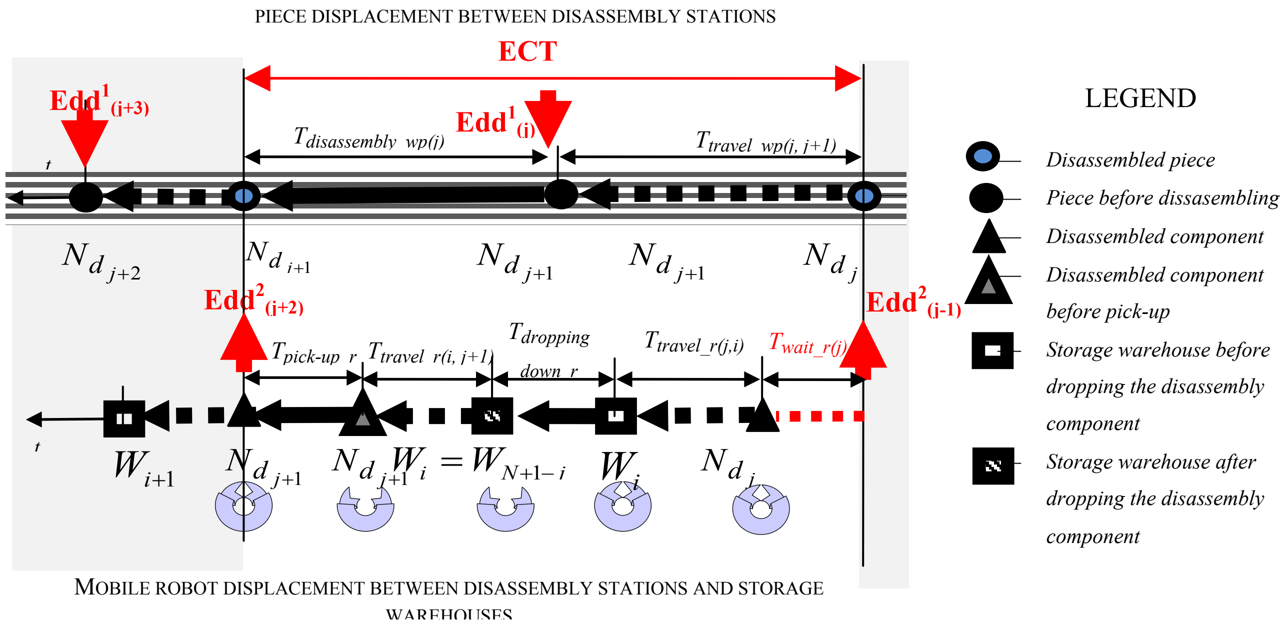
$$ETC_{R_j} = D(N_{d_j}, W_{N+1-j})/v_r + D(W_{N+1-j}, N_{d_{j+1}})/v_r + d_{dr_{3+(j-1)\cdot 4}} + d_{dr_{4+(j-1)\cdot 4}} \tag{16}$$

B. ECT in workpiece cycle time approach

The workpiece performed successive dispalcemets between disassembly stations. The actions STOP / START line disassembly, or START disassembly / picking up of disassembled component are triggered by external synchronization signals $E^1_{dd(j)}$ represent an external synchronization signal, corresponding to STOPPING / STARTING disassembly line. $E^2_{dd(j+2)}$ represent an external synchronization signals, corresponding to PICKING UP of disassembled component and STARTING line [11]. For the workpiece $T_{travel\_wp_{j,j+1}}$ is the travel duration between N_{d_j} - the disassembling location to $N_{d_{j+1}}$ - the next disassembling location. $T_{disassembly\_wp_j}$ is the duration of disassembly operation for j stage.



a)



b)

Fig. 6. Time intervals during elementary sequence of disassembly for a) $ECT_R > ECT_{WP}$; b) $ECT_R < ECT_{WP}$

The commands START disassembly is launched after the $E^1_{dd(j)}$ synchronization signal reception. During $T_{waiting\_wp_j}$ the workpiece expected (Fig. 6.a) the end of pick-up action performed by the mobile robot. In this case the elementary cycle time for the workpiece approach ETC_{WP} is:

$$\begin{cases} ETC_{WP_j} = T_{travel\_wp_{j,j+1}} + T_{disassembly\_wp_j} \\ T_{travel\_wp_{j,j+1}} + T_{disassembly\_wp_j} = \left(d_{dd_r} + d_{dd_{r+2}} \right)\Big|_{r=1+(j-1)\cdot 3} \end{cases} \quad (17)$$

The cycle time (CT) optimization for the mobile robot approach (Fig. 6.b) require the minimization of disassembly operations duration and the minimization of manipulation durations. Optimal value for the optimal time cycle becomes:

$$\begin{aligned} TC &= \sum_{j=\overline{1,N-1}} ETC_{R_j} + \sum_{j=\overline{1,N-1}} + T_{wait\_R_j} \\ TC &= \sum_{j=\overline{1,N-1}} ETC_{WP_j} + \sum_{j=\overline{1,N-1}} + T_{wait\_WP_j} \end{aligned} \quad (18)$$

At the same time it must be provided the temporal synchronization between $\min\left(ETC_{R_j}\right)$ and $\min\left(ETC_{WP_j}\right)$ for each j stage. From this condition results the optimal linear speed value ($v_{r\_opt_j}$) of the mobile platform displacement during j stage. For the SHPN model this restriction is equivalent to avoid the blockage for PN model:

$$\begin{aligned} \min\left(ETC_{R_j}\right) = {} & D\left(N_{d_j}, W_{N+1-j}\right) / v_{r\_opt_j} + \\ & D\left(W_{N+1-j}, N_{d_{j+1}}\right) / v_{r\_opt_j} + \\ & \min\left(d_{dr_{3+(j-1)\cdot 4}} + d_{dr_{4+(j-1)\cdot 4}}\right)\Big|_{j=\overline{1,N}} \end{aligned} \quad (19)$$

$$\min\left(ETC_{WPj}\right) = \min\left(d_{dd_r}\Big|_{r=1+(j-1)\cdot 3} + d_{dd_{r+2}}\Big|_{r=1+(j-1)\cdot 3} \right) \quad (20)$$

$$ETC_j = \max\left(\min\left(ETC_{R_j}\right), \min\left(ETC_{WP_j}\right)\right) \quad (21)$$

$$v_{r\_opt_j} = \frac{ETC_j - \min\left(d_{dr_{3+(j-1)\cdot 4}} + d_{dr_{4+(j-1)\cdot 4}}\right)\Big|_{j=\overline{1,N}}}{D\left(N_{d_j}, W_{N+1-j}\right) + D\left(W_{N+1}, N_{d_j+1}\right)} \quad (22)$$

$$TCO = \sum_{j=1}^{N-1} ETC_j \quad (23)$$

Conclusion

A cycle time optimization based on the optimization of elementary durations of disassembly sequences for the assembly/disassembly mechatronics line (A/DML) served by mobile robots. The elementary disassembly cycle is based on the simultaneous elementary sequence durations: the disassembling of the next workpieces parts and the warehouse displacement of mobile platform for storage previously disassembled component. The optimization of the cycle time is based on the synchronized events which appear in the SHPN model of A/DML served by WMB. The entire approach is useful for waiting time and the optimal speeds of mobile robot identifications. These will be used in the control implementation of A/DML served by WMR..

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