CONTROL ARCHITECTURE FOR RECONFIGURABLE AND DISTRIBUTED MANUFACTURING SYSTEM

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Abstract. *Control systems for conventional manufacturing systems are designed based on division in scope and control problems organized into hierarchical levels such as, enterprise control, factory control, and shop-floor control. However, currently manufacturing systems must assure integration and reconfiguration flexibility characteristics, i.e., a reconfigurable manufacturing system must collaborate each other, combining a global vision with a relatively agile reaction to unexpected variations of the shop-floor control level or new businesses processes in enterprise and factory control levels. On the other hand, in a global market, control systems must also consider businesses processes of geographically distributed manufacturing systems to take advantages of local facilities. Holonic and Multi-Agent System (HMAS) and Service-Oriented Architecture (SOA) techniques are effective to model control system of RDMS, but a formal method must also be considered to ensure this combination and a systematic application of design specifications. Therefore, this paper proposes models of control architecture for RDMS using bottom–up and top–down approaches through Petri net technique. This models extends a method to model a control system for RDMS based on combination of HMAS and SOA. Fault-tolerant control mechanisms and their application aspects are treated and an application example demonstrates advantages of this proposal, such as autonomy, flexibility, collaboration, reuse and robustness.*

Keywords: *manufacturing system; reconfigurable system; service oriented architecture; holonic and multi-agent system; distributed productive system*

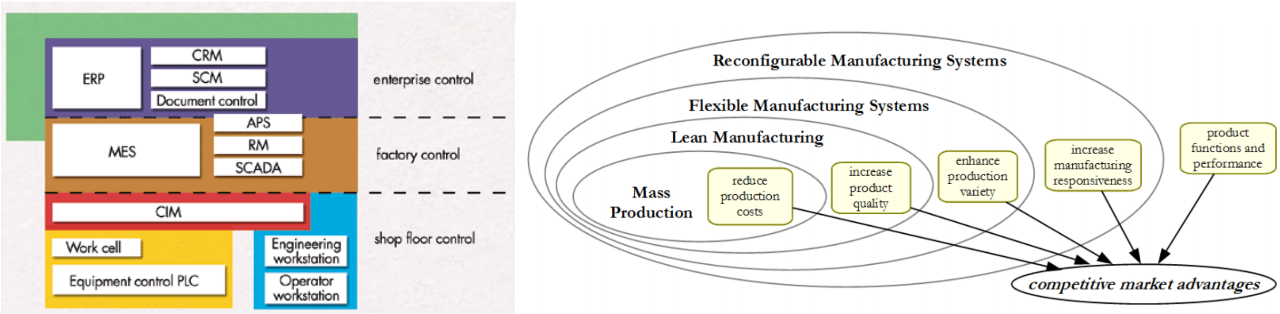
1. INTRODUCTION

Manufacturing systems have been designed to meet demands of goods production, transforming materials and processing information based on control functions. These functions were organized into hierarchical levels as Fig. 1a shows: *enterprise control* — where decisions and control are made in long-term management; *factory control* — where decisions and control are related to ordination of requests and supervision of productive processes; and *shop-floor control* — where decisions and control are machines operations, which are automatically executed through programmable controllers connected to sensors and actuators (Groba *et al.*, 2008).

The growing competitiveness and the need for efficiency imposed changes requiring greater flexibility under different aspects. The evolution is characterized by a gradual migration of manufacturing paradigms: mass manufacturing is concerned to cheaper products; lean manufacturing is concerned to continuous quality improvement; flexible manufacturing system is concerned to products diversity; and reconfigurable manufacturing system is concerned to be "adjustable" to business and market interests. Figure 1b shows economic goals associated with this evolution (Mehrabi *et al.*, 2000). Besides, control systems of distributed manufacturing systems in dispersed geographic location with different businesses processes (material transformation and/or information processing) must interact each other (Ali *et al.*, 2005; Garcia Melo *et al.*, 2008) to take advantages of local facilities and expertise.

Despite advantages of Reconfigurable and Distributed Manufacturing System (RDMS) paradigm, its implementation is not trivial. There is the need for increasing safety in machines and their controllers, adequate use of resources and for methods that allow qualified staff to update (or replace) legacy systems. Besides, a global vision of the system goal must be combined to autonomous components. These challenges, associated with the lack of quantitative performance data to evaluate these aspects, restrict the expansion of this paradigm (Vrba *et al.*, 2011).

For increasing safety, solutions based on Active Fault-Tolerant Control System (AFTCS) (Zhang and Jiang, 2008) involving fault detection, study of its effects, identification of its causes and finally, reconfiguration of the system through relocating and choosing alternative productive processes can be considered. According to Silva *et al.* (2012a), the control strategy must recover the functionality of the system (also called *regeneration*) or maintaining operations where parts affected by the fault are disabled without affecting operations in other parts of the system (also called *degeneration*). Therefore, to ensure that a RDMS meets all their purposes, their control systems must be updated for agile reaction both



(a) (b)

Figure 1. Each control level represented in classical manufacturing control architecture (a) involves functions control of businesses processes. At enterprise control level, there are Enterprise Resource Planning (ERP), Customer Relationship Management (CRM), Supply Chain Management (SCM) and document control functions. At factory control level, there are Manufacturing Execution System (MES), Advanced Planning and Scheduling (APS), Supervisory Control And Data Acquisition (SCADA) and Resource Management (RM) functions. At shop-floor control level, there are Computer Integrated Manufacturing (CIM), work cell, equipment control Programmable Logic Controller (PLC), engineering and operator workstations functions. In (b) the evolution of manufacturing systems associated to economic goals.

for unexpected variations of shop-floor control level (such as fault occurrence; and addition, replacement or exclusion of resources) as for variations of businesses processes in enterprise and factory control levels. In other words, a control system for RDMS must consider reconfiguration flexibility (da Silva *et al.*, 2014b).

For adequate use of resources, a method to model control system must also avoid repetition of tasks and overlapping of project scope through reuse models, ensuring through formal models the implementation of design specifications, interoperability and collaboration among its entities (Tommila *et al.*, 2005). Holonic Multi-Agent System (HMAS) can allow conception of an intelligent control component (agent) (Ferber, 1999) for RDMS. Moreover, the agent-based control software, which is part of the resource, can be endowed with communications and information processing capabilities, transforming it into a self-reconfiguring, intelligent element, i.e., a holon (Koestler, 1968). The result is a distributed intelligent automation system associating hierarchical and heterarchical control (Colombo *et al.*, 2001).

The control system for RDMS must also consider collaboration activities among distributed subsystems that compose whole manufacturing system. According to Han *et al.* (2008), the service oriented architecture (SOA) is an effective solution for this. In SOA, an integration level is introduced among the *factory control* and *shop-floor control* levels. The integration level is a middleware which has available application tools and interfaces to communicate with other applications in other levels. Mendes *et al.* (2009) explain how to combine the service-oriented agents in industrial automation, sharing resources in the form of services by sending requests among agents. Nagorny *et al.* (2012) proposed the use of hardware and software accessed remotely via communication network, and where operational activities are described as services. Other studies presented new perspectives about how to combine the SOA and HMAS concepts, but there are few publications proposing a method based on formal technique (formal method).

In previous studies (Silva *et al.*, 2012a,b), HMAS was combined with AFTCS and resulting system was applied in intelligent buildings, which is another important class of productive system. In Silva *et al.* (2012c, 2011), the focus was on reconfiguration mechanisms for agile reaction based on control mode switching (among two operational modes). In da Silva *et al.* (2014b,a) different aspects about joining SOA and HMAS concepts are introduced. In the light of the foregoing, this paper extends the method to model a control system for RDMS based on combination of HMAS, SOA and Petri net (Murata, 1989), focusing on description control architecture and modeling fault-tolerant mechanisms and their application aspects. To describe the models, Petri Net (PN) is used to validate manufacturing control system due its advantages on graphical and formal representation, analysis and simulation tools, and similarity to controller language. This paper has following structure: in Section 2 the control architecture is presented; in Section 3 the control architecture and an application example are presented; and in Section 4 are the main conclusions.

2. CONTROL ARCHITECTURE FOR RDMS

A RDMS can be approached as a class of discrete event system. Therefore, PN and its extensions are adequate for description its behavior (Murata, 1989). Specifically, this work adopts a channel/agent PN type called Production Flow Schema (PFS) (Miyagi *et al.*, 1988) for conceptual description of the system, and an Extended place/transition PN (E-PN) in which `temporized transitions`, `inhibitor arcs` and `enabling arcs` (terms related to PN are in `Typewriter`) were added (David and Alla, 1994) for functional description of the system. The idea is combine bottom-up approach from the productive processes models in E-PN, and the top-down approach of stepwise refinement associated to PFS models of the system's activities associated with o flow of discrete items (information or material).

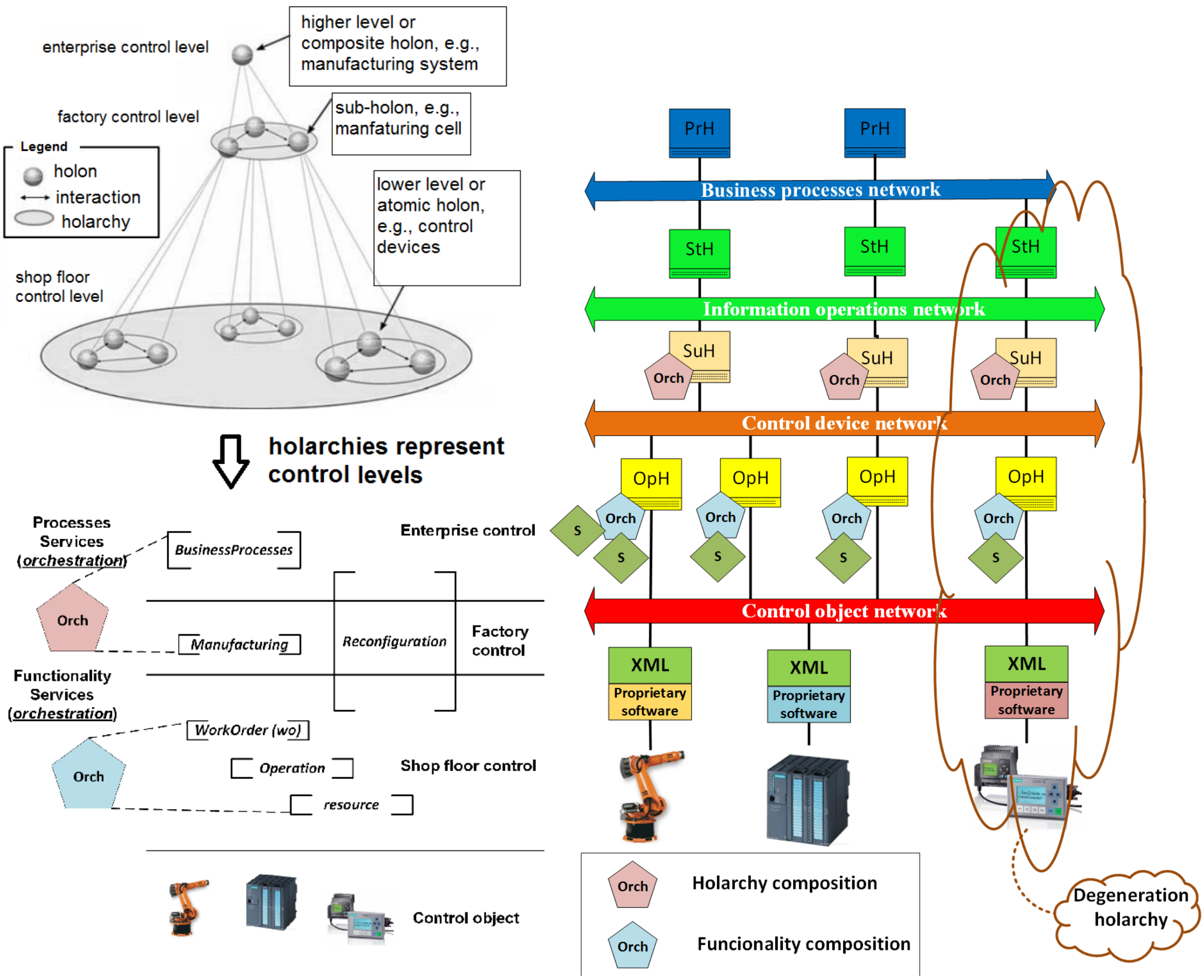


Figure 2. Holonic concept applied to manufacturing system and proposed control architecture.

Figure 2 shows an example of holonic abstraction (Colombo *et al.*, 2001) for manufacturing system. A holon can composite larger holons or being decomposed in atomic holons. They should have characteristics of autonomy, recursion and collaborating and interact with same level and with holons of higher or lower levels. The interactions vary from simple information exchanges through requests to perform a particular operation until complex negotiations. The proposed architecture considers the following holons:

- *product holon (PrH)* which contains the necessary knowledge for the general operation of RDMS and choosing the general strategy that attains the planned objectives. Each *PrH* has an internal process flow, the required input types and output types. The *PrHs* represent the products of the RDMS which can be intermediates if there is some manufacturing operation to get the final products;

- *strategies holon (StH)* which contains the knowledge to manage the execution of the strategies to attend the requests (market demands);

- *supervisor holon* (*SuH*) which contains all the knowledge to coordinate holons of lower hierarchical levels, registering the abilities of each component and providing services combined with other entities of the control system; and

- *operational holon* (*OpH*) which represents the RDMS physical resources (operators or equipments) that have specific control devices for its automatic operation, and determines the behavior of these resources in accordance to its objectives and abilities.

The structure and relations among these holons are showed in Fig. 3 according to the UML class diagram (Booch *et al.*, 2005) and specification of HMAS (FIPA, 2002).

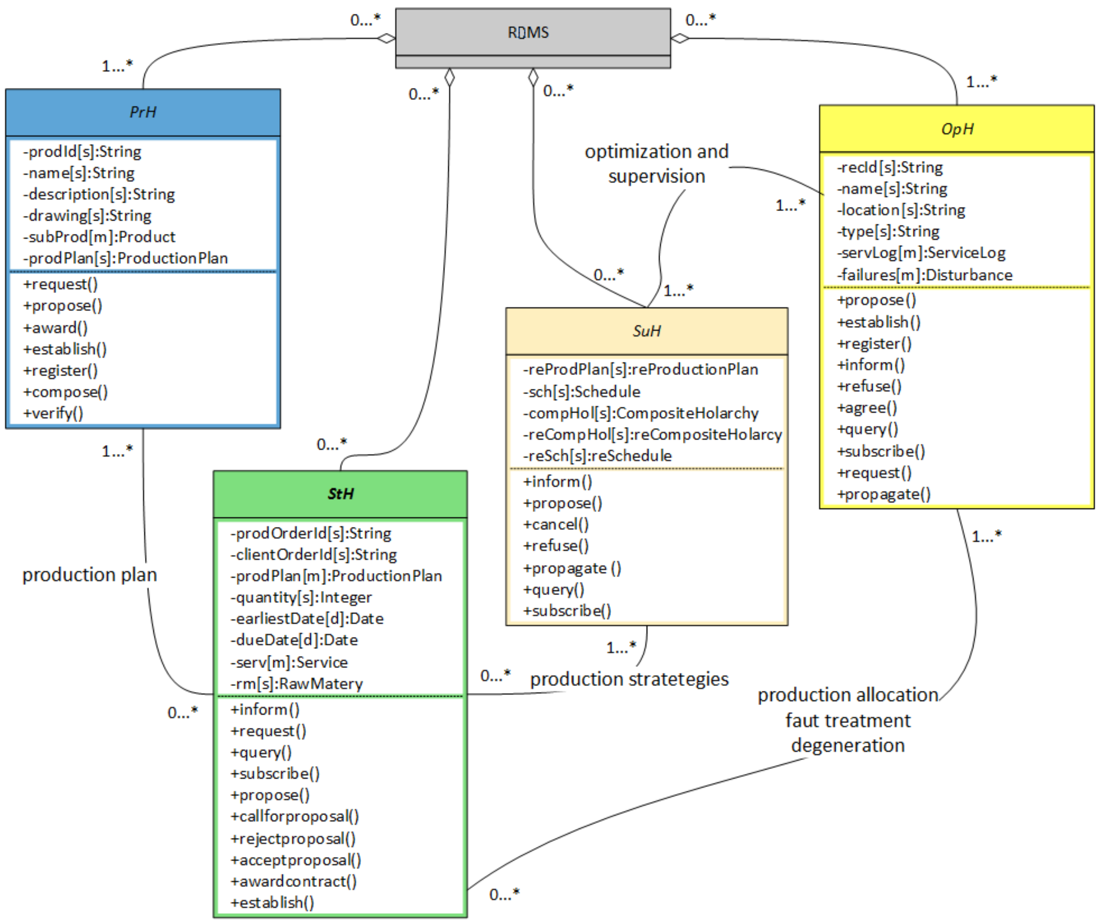


Figure 3. UML class diagram of the holons, following the specification of FIPA.

To process a production order, a holarchy represents a *business processes* (see left in Fig. 2). These holarchies are created based on collaboration of holons, providing a middleware for integration among the control levels. A holon can belong different holarchies of different control levels. The challenge is to determine the best holarchy formed to fulfill the production order based on the available resources. To achieve this objective, the proposal is based on negotiation, CNP and ABC. For instance, considering that E-PN models are used to represent workflow satisfying certain timing constraints, using the `temporized transitions` in E-PN models (or other cost variable) can be made holarchy composition in a automatic manner. Let us consider that $[H_n]$ is a production sequence n in the RDMS formed by *PrHs* to obtain the final product. Let us consider the following sequences: *$[H_1]$: [A0]$\rightarrow$ [A1]$\rightarrow$ [A2]$\rightarrow$ [B0]$\rightarrow$ [B1]$\rightarrow$ [B2]$\rightarrow$ [A2+B2]* and *$[H_2]$: [A0]$\rightarrow$ [A3]$\rightarrow$ [B0]$\rightarrow$ [B3]$\rightarrow$ [A3+B3]*. Let us suppose due date set by *PrH-[B2]* is t_e*[B2]*. This order due date imposes a timing constraint on *PrH-[B1]* in sequence of $[H_1]$. Let t_e[B1] be the latest time that *PrH-[B1]* must complete all its operations. Let $t_e[t_n]$ be the time that `transition` n must complete its operations. To meet the due date, constraint of Eq. (1) must be satisfied by *PrH-[B1]* and so on for another holons.

$$t_e[B1] \leq t_e[B2] - t_e(t_{18} + t_{19} + t_{20} + t_{21} + t_{22}) \quad (1)$$

Let us associate a variable named cost to H_n or *PrH* for holarchy composition. Let C_N be the cost of a production sequence N of a H_n or a *PrH*. Let c_n be the cost of a `transition` n of E-PN model. To compose holarchies the sequence that offers the shortest cost should be chosen. In example, cost of C_{H1} and C_{H2} should be compared in automatic manner to decide what is the best sequence for production, according Eq. (2) and Eq. (3). The c_n for each *PrH* is calculated according to the case for *PrH-[B2]* in Eq.(4).

$$C_{[H1]} = C_{[A0]} + C_{[A1]} + C_{[A2]} + C_{[B0]} + C_{[B1]} + C_{[B2]} + C_{[A2+B2]} \quad (2)$$

$$C_{[H2]} = C_{[A0]} + C_{[A3]} + C_{[B0]} + C_{[B3]} + C_{[A3+B3]} \quad (3)$$

$$C_{[B2]} = c_{t18} + c_{t19} + c_{t20} + c_{t21} + c_{t22} \quad (4)$$

The application of fault-tolerance concept is divided into four phases in each holon independently of hierarchical level. The "estimation phase" involves symptoms detection and faults isolation for identification. The reconfiguration is decided

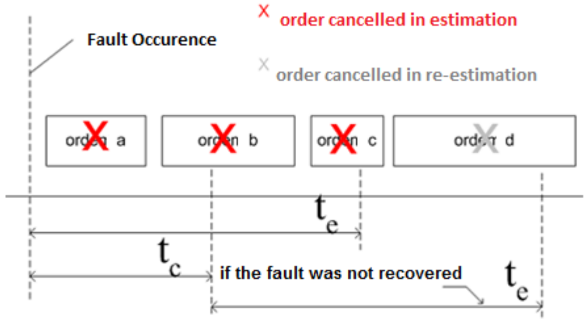


Figure 4. Estimation of the reconfiguration time

Table 1. Negotiation of control system for RDMS based on CNP, adapted from Smith (1980) .

HCP	StHs	OpHs
Operation allocation process.	Contracts the operation execution by ξ and the penalty by φ.	Contracts the operation execution by ξ and the penalty by φ.
Finish of an operation with success.	Pays the value ξ to the OpH (π ← π − ξ).	Increases the total credits by ξ (μ ← μ + ξ).
End of an operation with delay	Pays the value ξ and receives the value φ from the OpH (π ← π − ξ + φ).	Decreases the total credits by φ and increase by ξ (μ ← φ).
Operation cancelled (delay, failure, etc.)	Receives the value φ from the OpH (π ← π + φ).	Decreases the total credits by φ (μ ← μ − φ).

in “planning phase”, which is based on predefined priorities and on historical data, such as statistical significance each type of fault in terms of frequency rate, recovery time, and operational cost. The “execution phase” involves sending commands for the execution of the selected action plan. The last is “learning phase”, which involves the storage relevant data to be used in further cases. Therefore, this control system acts according to the following rules:

- *if <symptoms> then <selects fault>*;
- *if <selected fault> then <selects action>*;
- *if <selected action> then <activates reconfiguration>*; and
- *if<executed reconfiguration> then <store relevant data>*.

In fault occurrence, the holons propagate messages to ensure agile response to faults. The holon that detected fault sends this information to *SuH* starting the propagation of messages and indicating the need for reorganization. *StHs* receive this message propagating to neighboring holons. To prevent accidents, a degeneration holarchy (as illustrated in the right of Fig. 2) can be formed allowing quicker reaction if the fault treatment does not solve the problem.

Figure 4 illustrates how to estimate reconfiguration time. If the resource affected by fault becomes unavailable for long period, *OpH* estimates the recovery time (t_r), checks planned orders during this period and cancels current allocation these orders notifying *StH*. For this, *OpH* estimates two different parameters: t_e, time that the order return to *StH*; and t_c, time to check if the fault was recovered, re–estimate and re–apply time parameters, if the fault was not recovered as expected. To calculate these two values, t_r is determined based on spent in the previous treatment faults and on this time, 50% for t_c and 90% for t_e are increased. If the fault is not recovered, time parameters are re-estimated and planned orders for this new time interval (obtained by $t_c + t_e$) are canceled . During time that the resource is unavailable, *OpH* only receives new commands if they can be run outside estimated range for recovery time.

The negotiation mechanism is based on Contract Net Protocol (CNP) (Smith, 1980) and Activity-Based Costing (ABC) (Cooper, 1988). These rules allow negotiation among holons based on credits (rewards) and fee (penalties) depending if work order is completed in due time or not. When *StH* is responsible for implementing a particular strategy, it receives the following information of *PrH*: chosen strategy; quantitative measure named “order production fund” (π); scheduled time; penalty for delay (φ); and reward value (ε) to be finalized successfully. The *StH* should manage negotiation to *OpHs* for achieving goal without exceeding the service fund; and in resource allocation, regarding the performance of them given by μ. Table 1 summarizes the evolution of this mechanism.

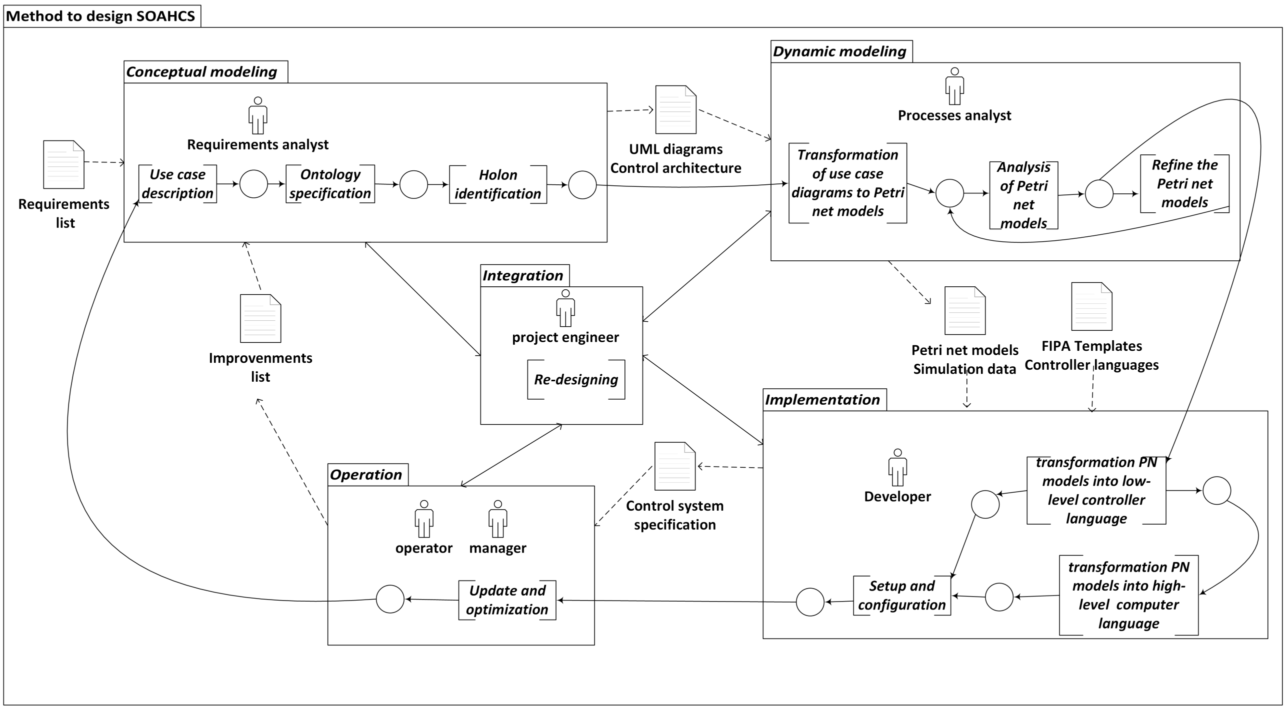


Figure 5. Schema of the method to design control system for RDMS, using PFS and UML techniques.

The “diagnoser” and the “decider” fulfill requirements of fault-tolerant control for diagnosis and decision phases. The steps to design these E-PN models are:

- construction E-PN models for control objects;
- construction of E-PN models for control strategies;
- definition of observable events, generally those related to control strategy commands; and non-observable events, generally related to faults – see Sampath *et al.* (1996);
- construction of E-PN models of sensors;
- initiating construction of “diagnoser” from initial state considered “normal” (without faults);
- relating, by means of `transitions` and `enabling arcs`, performed strategies to possible observable and non-observable events which may happen from initial state; and
- relating states obtained to states of sensors. If “diagnoser” does not indicate correct state then possible faults’ causes must be inferred to solve possible conflicts. This decision mechanism is called “decider” and its decision making rules may be based on probabilistic data, for example.

3. CONTROL ARCHITECTURE DESIGN FOR RDMS

This Section presents models of the method since initial conception until operation phase of the proposed control architecture (Fig. 5). Each phase involves *actors*[1], the utilized and generated *artifacts* which are detailed as follows. The *phase 5 – integration* – ensures a closed-loop to manage the re-designing of the other phases. In the following explanation, an application example of benchmark RDMS, illustrated in Fig. 6, is also presented. As cited, this paper focus on description control architecture and modeling fault-tolerant mechanisms and their application aspects, for detail about the method see da Silva *et al.* (2014b,a).

In *conceptual modeling phase*, specifications are defined: aim of the system, control object, control devices, definition of tasks, strategies and control functions, description of interaction among parts of the system, and cases of reconfiguration. The benchmark RDMS is composed by six workstations WSs that represent autonomous subsystems: distributing workstation $(D - WS)$, testing workstation $(Te - WS)$, transporting workstation $(Tr - WS)$, handling workstation $(H - WS)$, assembly workstation $(A - WS)$ and robot workstation $(R - WS)$. Work orders (wos) can be executed on each WS which has its respective controller and operates independently as a stand-alone industrial plant. Each controller

[1] Terms related to SOA technique are *underlined*.

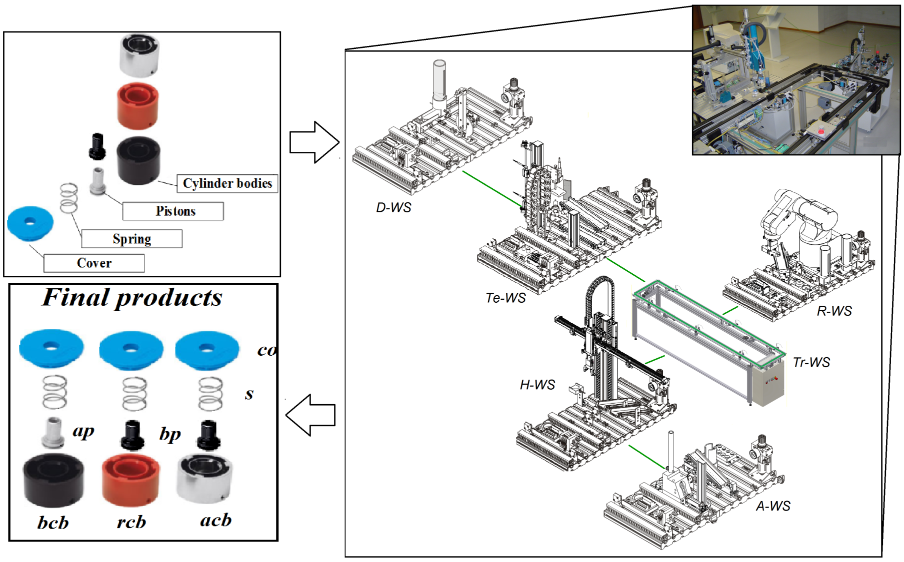


Figure 6. Benchmark reconfigurable and distributed manufacturing system.

Table 2. Devices and their functions list of $D - WS$, which are identified according to DIN/ISO 1219-2:1996-11 and IEC 61346-2:2000-12. For example, in the nomenclature "$1S2$": 1 =circuit number, S =device code, and 2 =device number.

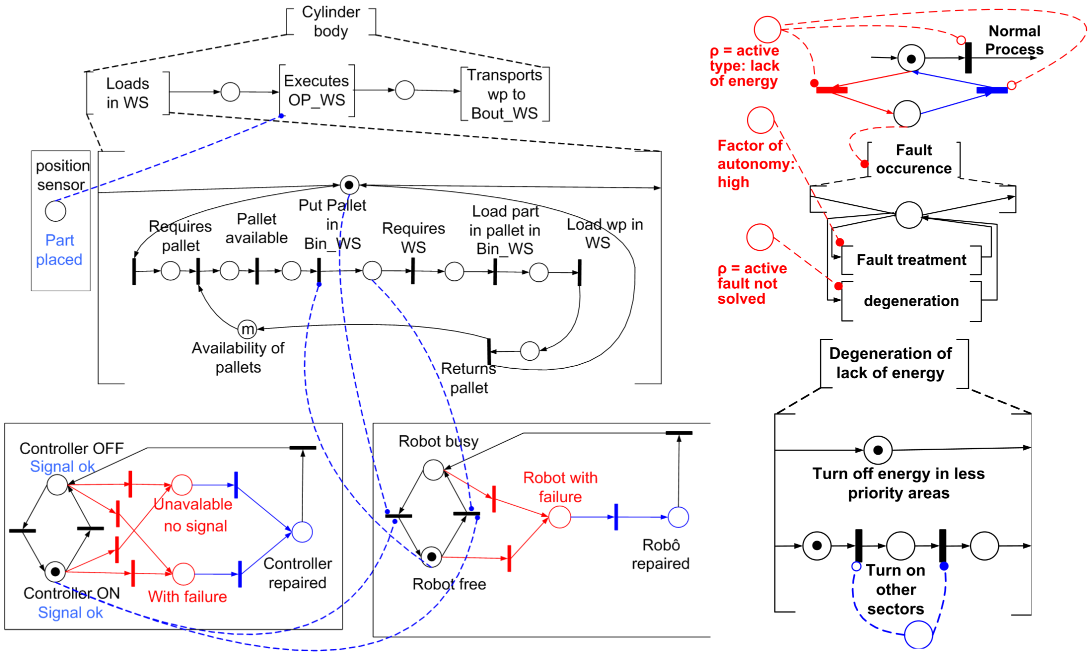
Nomenclature	Function	Device
1A	removes the workpiece cylinder body of the buffer	pneumatic cylinder double acting
2A	takes the wokpiece cylinder body	vacuum generator and sucker
3A	transports the workpiece cylinder body to the next workstation	pneumatic rotary actuator
1Y1	It modifies the state of the valve-1 for piston retreating position	solenoid
2Y1	It modifies the state of the valve-2 for vacuum generator that activate position	solenoid
2Y2	It modifies the state of the valve-2 for vacuum generator that deactivate position	solenoid
3Y1	It modifies the state of the valve-3 for swivel arm in supply workstation	solenoid
3Y2	It modifies the state of the valve-4 for swivel arm in testing workstation	solenoid
1B1	It detects the piston retreated position	magnetic proximity sensor
1B2	It detects the piston extended position	magnetic proximity sensor
2B1	It detects if the suction gripper caught a workpiece	vacuum sensor
3S1	It detects if the swivel arm is in the testing workstation position	electrical switches limit
3S2	It detects if the swivel arm is in the distributing workstation position	electrical switches limit
1B4	It detects the lack of the workpiece in the magazine	optical sensor

is connected to the internet allowing operators and clients interact. The aim of benchmark RDMS is automatically assembling products composed of workpieces (wps): a cylinder body (black $[bcb]$, red $[rcb]$ or aluminum $[acb]$), a piston (black $[bp]$ or aluminum $[ap]$), a spring $[s]$ and a cover $[co]$. The aluminum piston is assembled only on black cylinder body while black piston is assembled on red or aluminum cylinder bodies. Springs and covers are the same in all assemblies. Furthermore, final products are: $[bcb + ap + s + co]$; $[rcb + bp + s + co]$; and $[acb + bp + s + co]$. Each workstation processes the wps at each time, and has buffers with limited storage capacity, besides another resources. Control devices, their control functions, commands and signals for actuation and detection should be identified. The identification is made according to DIN/ISO 1219-2:1996-11 (DIN – Deutsches Institut für Normung)/(ISO – International Organization for Standardization) and IEC 61346-2:2000-12. Table 2 shows the proper primitives to perform the control task for $D - WS$.

Recursive structure (holons made up of holons) allows designing each holon to figure out the advantages of decomposing it into a new holarchy. This process is repeated until every holon is completely defined and there is no need for further decompositions. Holonic processes are production workflow created dynamically and based on the collaboration of the holons. Each *PrH* represents a product and has an internal process flow, the required input types and output types. There are the intermediate *PrHs:* $[bcb]$, $[rcb]$, $[acb]$, $[ap]$, $[bp]$, $[s]$, $[co]$, $[bcb + ap]$, $[rcb + bp]$, $[acb + bp]$, $[bcb + ap + s]$, $[acb + bp + s]$, $[rcb + bp + s]$ and there are three final *PrHs*: $[bcb + ap + s + co]$, $[rcb + bp + s + co]$ and $[acb + bp + s + co]$.

The synchronization of E-PN models is made by `enabling arcs` and `inhibitor arcs`. The following interactive processes are considered in the modeling: request products, implementation services, fault treatment and reconfiguration. These processes are described using UML diagrams (Booch *et al.*, 2005) and the proposed CNP protocol, following the specifications of FIPA for HMAS.

In *dynamic modeling phase*, the PN models are created based on preview specifications. Figure 7 illustrates modeling examples: Fig. 7a shows models of product order for a cylinder body workpiece and following sub-models: PFS of the



(a) Plan production $wp[cb]$ and control objects models (b) Fault treatment and degeneration models

Figure 7. Examples of modeling

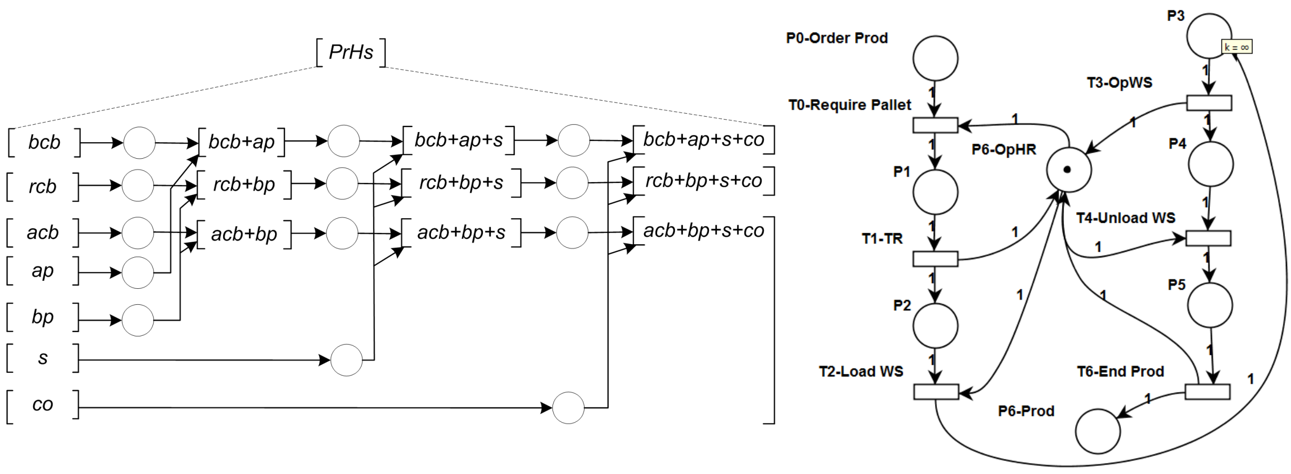
production plan, E-PN of [*executesOp_WS*] of robot and its controller. E-PN models consider influence of transmission of control signals and the faults states. Figure 7b presents examples for fault treatment and degeneration.

Figure 8a illustrates PFS of global production process, representing the combination of intermediates *PrHs* to get final *PrHs*, and the required input types and output types among them. To model workflow of a *PrH*, a `place` represents a state while a `transition` represents an event or operation that brings the flow from one state to other. Figure 8b exemplifies this flow for *a PrH*.

Figure 9 represents the E-PN and the list of conditions (`places`) and actions (`transitions`) to the control process of $D-WS$.

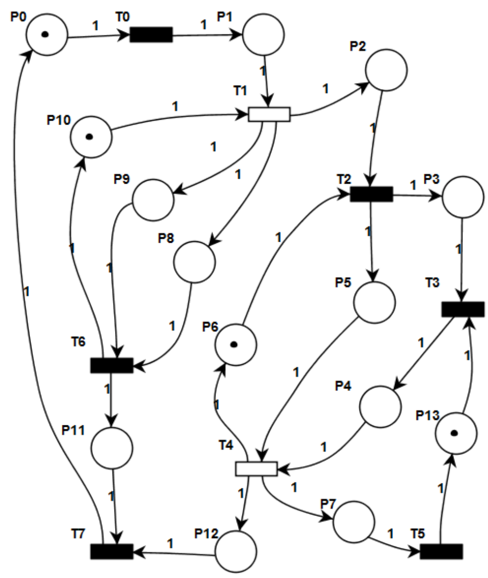
Figure 10 shows valve 1 component commanded by *OpH*, PFS and E-PN models of valve 1 model considering the influence of the control signal transmission network, diagnoser for valve 1, flowmeter, and the related decider device.

Analysis of the structure and the dynamic behavior are based on E-PN properties. Qualitative analysis is based on structural analysis of the E-PN models. Quantitative analysis is performed through simulation of E-PN with `timed transitions`. This analysis uses PIPE software (Bonet *et al.*, 2007) and allows re-designing and re-engineering control system during design phase. Scenarios are also identified and models are built for each case. These models must meet the restrictions and achieve the objectives outlined in the hypothesis. Furthermore, they revise the control system models and



(a) Global production (b) Workflow process of a PrH

Figure 8. Production process



place/ transition	description
P0	station ready
P1	workpiece sensor detects the presence of the buffer
P10	valve energized to indent the pneumatic piston
P11	pneumatic piston retreat
P12	workpiece in magazine
P2	workpiece positioned to be removed from the next station
P3	swivel arm positioned on the D-WS
P4	suction gripper caught workpiece
P5	valve energized to position swivel arm over D-WS
P6	valve energized to position swivel arm over Te-WS
P7	swivel arm positioned on the Te-WS
P8	Extended pneumatic piston
P9	energized valve to extend pneumatic piston
T0	receives order production
T1	advancing pneumatic piston to remove the workpiece of the buffer
T2	energizing valve to move the swivel arm to magazine of D-WS
T3	energizes the valve that connects the suction
T4	move between stations the swivel arm
T5	deenergizes valve that connects the suction
T6	retreat the pneumatic piston
T7	free D-WS for new cycle

Figure 9. E-PN for control process of $D - WS$. Initial conditions must be attended to start the station.

identify the `places` and `transitions` that must be attended in each service.

For practical use, in *implementation phase,* resulting models are interpreted as control program specifications to be performed by computers (supervisory control level) and programmable controllers (local control level). Allocation of control signals associated to programmable controllers should be listed. For low-level control applications, code generation is made following IEC60848 GRAFCET language, a wide used programmable controller language. For high-level language, code is made in Java using JADE (Java Agent Development Framework) (Bellifemine *et al.*, 1999), framework fully implemented in JAVA language. Figure 11 shows implementation and JADE fragment code examples. Figure 12 shows GRAFCET to control the $D - WS$.

In *operation phase,* real-time monitoring system for supervision and control is accomplished by synchronizing operation of E-PN models with sensor signals that represent the device's state. Depending on role of user involved, accessible functions and user interfaces must vary. For example, an administrator is responsible for the user's account. An order manager is responsible for creation of *StH* and re-initialization. A product manager is responsible for definition and creation of *PrHs*. A resource manager is responsible for updating *OpHs*.

Proposed architecture control allowed the negotiation among holons and reconfiguration of different productive scenarios with safety and correctness during operation. Comparing conditions and actions that need to be met in each service, with `transitions` and `places` of E-PN models facilitated a systematic location of fault. Reconfiguration was not only applied to resolve occurrence of faults but also to improve the system's performance by increasing production gain or number of final products. For example, by controlling speed of resources through the pneumatic pressure control and disabling swivel arm (represented for *OpH*-[sa_{D-WS}]) its function was assumed through *OpH*-[$R - WS$].

4. CONCLUSIONS

This paper presents a control architecture extending a method to design Reconfigurable and Distributed Manufacturing System (RDMS), describing required data. This method combines Service-Oriented Architecture (SOA) with Holonic and Multi-Agent System (HMAS) techniques. This control architecture is part of a method which integrates the design of the entire life cycle of control systems for RDMS; combines bottom–up and top–down approaches using extensions of Petri Net (PN): the Extended PN (E-PN) for functional description and production flow schema (PFS) for conceptual representation; has mechanisms for quicker reaction to faults, i.e., reconfiguration and degeneration mechanisms ensuring implementation of a hierarchical or heterarchical control structure; and proposes solutions to HMAS, such as, a mechanisms to holarchy composition problem and better collaboration of the holons based on contract net protocol. Furthermore, the control architecture has product-oriented and machine-oriented characteristics to facilitate implementation and operation. These characteristics contribute for technological innovation in control design presenting various advantages, such as autonomy, flexibility, collaboration, reuse and robustness.

Different scenarios were elaborated for running an application example of manufacturing system that emulates a RDMS. The control system responded in faster and collaborative manner and it is useful for protecting the system when hardware problems occur as implementing different thresholds of production. Therefore, operational advantages were

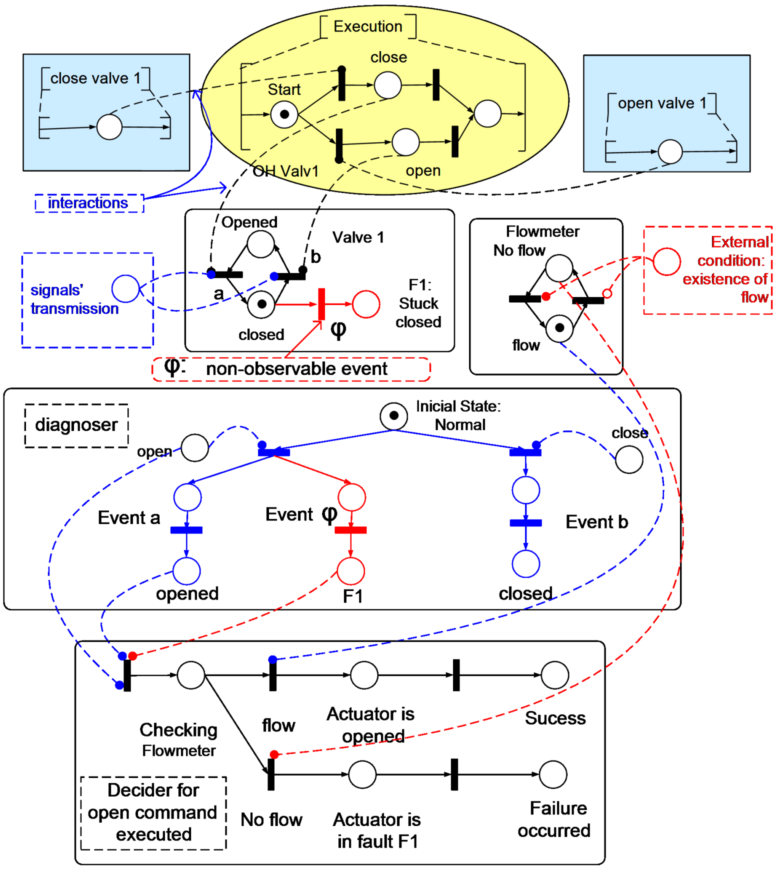
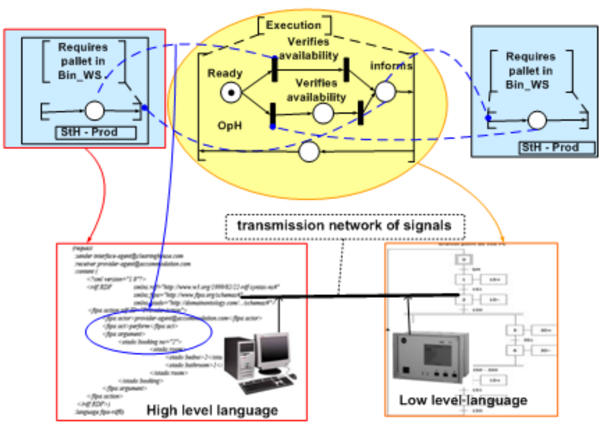


Figure 10. Diagnoser example. Based on control strategy and non-observable event (φ) occurrence, this diagnoser indicates possible states for making decision which in turn is based on inference roles. In this example, decision is based on verification through flowmeter, if it indicates "No flow" fault (F1 - "Stuck closed") is diagnosed for valve 1 of $D-WS$.




```
public void action() {
ACLMessagemsg = myAgent.receive();
if (msg != null) {
ACLMessage reply = msg.createReply();
        String content = msg.getContent();
if (content.equalsIgnoreCase("Is it possible to produce product A?")) {
reply.setPerformative(ACLMessage.INFORM);
reply.setContent("I will verify if there is any palet available");
myAgent.send(reply);
System.out.println("The seller "+msg.getSender().getName() + "ordered a product A");
System.out.println("OpH-P:Production Started");
}else{
if(content.equalsIgnoreCase("Paletavailable.Starting Production")){
          String content2 = msg.getContent();
System.out.println("-->"+msg.getSender().getName()+":"+content2);
}else{
if(content.equalsIgnoreCase("Palet is busy")){
            String content2 = msg.getContent();
System.out.println("-->"+msg.getSender().getName()+":"+content2);
```

Figure 11. E-PN models are interpreted as GRAFCET language or as JAVA language for higher control level.

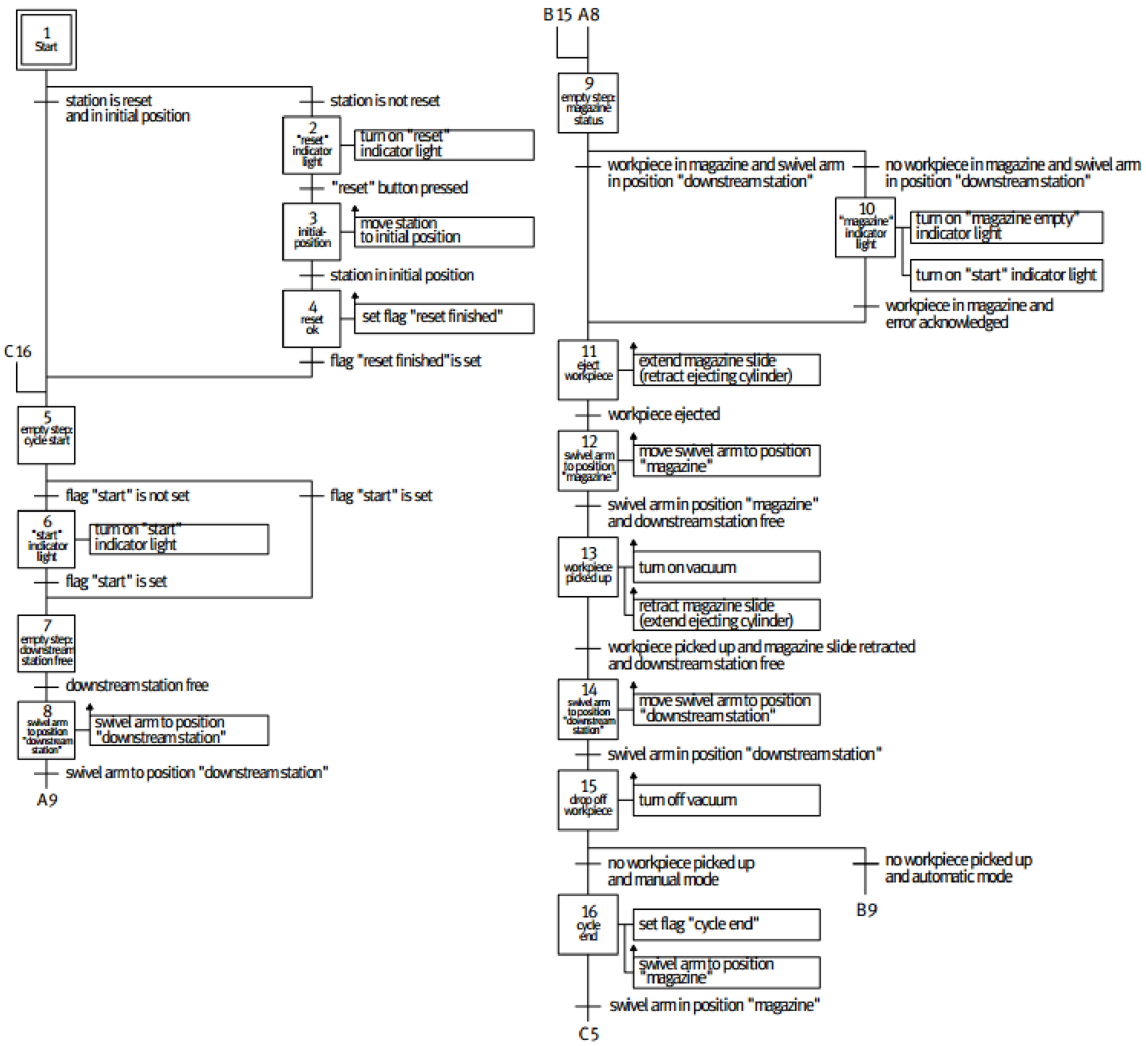


Figure 12. GRAFCET to control $D-WS$. Petri net models facilitate implementation because are similar to this language.

demonstrated such as, better and more efficient use of manufacturing resources, speed of production and ability to deliver products faster. As demonstrated in Silva *et al.* (2012a,b) the method and its control mechanisms and concepts can be tailored for other productive systems.

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