Modeling a Water Bottling Line Using Petri Nets

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***Abstract* - In the paper a bottling water line in plastic containers is presented, for which the authors have achieved a Petri Nets model that illustrates the whole system dynamic in various real working conditions. For heuristic representation of the model, several sequences and rules were, however, followed. First, in order to achieve a primary topology of the model was used a bottom-up synthesis technique, after which it was obtained a basic version created by submodels aggregation of related subsystems of the station structure. Interconnecting of these partial models was made in accordance with the interactions of the physical elements of the whole system, laid down in the operation protocol. Hence, were used into model topology various elements characteristic to generalized Petri Nets, with inhibitor arcs and test arcs, mainly aiming to reduce the complexity of the whole model. The verification of the model was done through on-line simulation under the Visual Object Net++ tool, which offers many facilities for the analysis of behavioral properties in various real operating conditions of the real physical system. Refining of the model can be easily achieved in a second step of the synthesis, by bottom-down synthesis techniques. Starting on the modular structure of the whole model, composed of sub-models very similar as topology, it can achieve its multilevel architecture, using Object Petri Nets paradigm for representation and exploiting their analysis potential.**

Keywords - ***discrete event drive systems; hybrid systems; model approximation; Petri Nets; simulation.***

I. Introduction

A hybrid dynamic system can be described like an abstract system with both continuous and discrete components interacting. Traditionally, such a system is either modeled as a continuous – state system or a discrete – state system driven by time or asynchronous external events.

Various artificial structures can be classified as hybrid systems, including logic – based switching control systems, intelligent transport systems, flexible manufacturing lines, batch processes and many other electromechanical systems (power electronics, robotics, flexible manufacturing systems, control of the electrical drives, hydraulics and pneumatics systems etc.). It is not suitable to model them as pure continuous – state or pure discrete – state systems, so that, in these cases, a hybrid system model is proposed to be quite powerful both for representation and for analysis. On the other hand, it's obvious that in a complex system there could be a great number of distinct system states that, organized in the finite state machine formalism manner, leads to complicated state diagrams [1], [2], [6], [15], [16], [17], [18], [20].

For the last past years, there has been a growing interest in dynamic systems that feature both continuous time and discrete event behaviors. The recent research has been determined by the growing need to use advanced and formal methodologies and techniques for modeling, simulation and control of hybrid systems.

Research and development over the last decades have provided new theory and formal tools based on Petri Nets (PN) and related concepts for the design of supervisory process controllers. PN have been primary applied to represent discrete systems, especially when many processes evolve concurrently and share common resources, as in manufacturing processes. Thus, as a visual formalism, PN was used for the specification and modeling of complex reactive systems, expanding finite state machine formalism with hierarchy, parallelism and broadcast communication.

Hence, in our paper generalized discrete PN models interest us. We limit our attention to describe a water bottling line by a non-autonomous model and to verify its behavioral properties by on-line simulation in order to propose a possible structure of the process controller [1], [2], [3], [4], [14], [18], [19], [20].

II. System Structure

The hybrid system which will be modeled in the following is an automatic plant for bottling water in plastic containers, whose structure contains three separated workstations, arranged in a serial production line: the transfer-loading station, the filling machine and the screwing cap station (Fig.1).

The whole plant line is a concurrent and flexible system. Each work station is composed of electro-pneumatically drives systems devices with double-acting cylinders as actuators. After recipients filling, their screw is realized with an air-feed pneumatic motor. All cylinders are driven by directional control discrete valves, commanded through sensors output signals. There are two sensors type: magnetic sensors, directly jointed on the pneumatic cylinders body and detection sensors located in various station points.

A. The transfer-loading station

The transfer-loading station consists in a continuous supply conveyor – B_1, which carries out the empty recipients from a central storage. The structure is also composed of a double acting pneumatic cylinder – A and its control valve – DA in order to transfer each recipient on the main conveyor – B_2, towards filling and screwing cap stations.

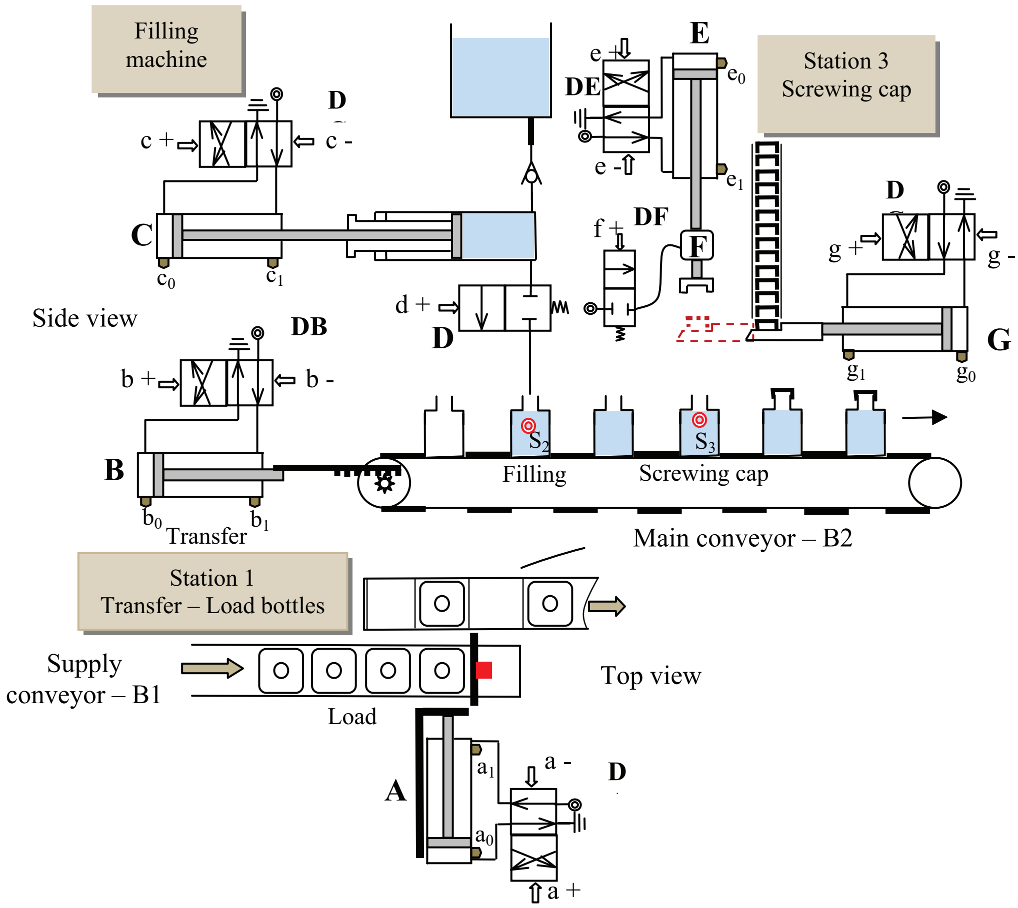

Fig. 1. Structure of automatic bottling plant.

The presence of each recipient at the end of the supply conveyor is detected by S1 (Fig. 1) which commands (a+) the control valve DA for the advance of A cylinder.

B. The bottling machine

The bottling machine (Fig.1) consists in a double acting cylinder C, commanded by a bi-stable control valve-DC. The cylinder piston moves inside a volume batcher, gravitational filled with water from the central tank. A mono-stable control valve D is mounted at the volume batcher output; its function is a bi-positional command which closes/opens the water filling circuit. Also a directional valve – S to ensure the directional flow is present in the circuit. At the moment that an empty recipient was transferred on the main conveyor, a1 is activated and commands the advance of B cylinder. The steeping wheel of B2 conveyor allows its movement on a length equal with the maximum B-cylinder stroke and assures in this way the transport of the recipient towards bottled device. At the end of stroke, b1 output commands the DB control valve and therefore the B-cylinder returns to its initial state. The presence of an empty recipient under the bottled device is detected by S2 sensor, which stops the transfer-loading activity during the entire bottled operation. The S2 active output allows controlling valve (D) to commute in “open” state and, in the meantime assures DC commutation such as C cylinder moves on for a complete volume batcher emptying. At the end of its active stroke, the sensor c1 switches and cancels the D and DC control valve commands. Hence, the cylinder C returns at its initial state, when by sensor c0 activation the transfer-loading station restarts. A new empty vessel is ready to be filled in the same way. The operations sequence described above repeats until the first filled recipient stops under the screwed cap station and the sensor S3 is activated.

C. The screwing cap station

The screwing cap station (Fig.1) contains two double acting cylinders (E and G), driven each of them through a bi-stable control valve (DE and DG respectively). Also, a pneumatic motor (F) and a control valve (DF) complete the station structure. All the caps which will be screwed to filled vessels are stored in a transfer device, where, by gravity, are then taken and placed above the vessels by the G - cylinder blade. Both pneumatic motor – F and the gripper caps device are together and fitted jointly at the E cylinder plunger. The sequence of operations performed on this station is: advance of G cylinder, then advance of E cylinder until the gripper takes one vessel cap, return of both G and E cylinders at their initial position, then the complete stroke advance of E cylinder to fix the cap above a fill vessel, the cap screwing and, finally, return of E cylinder in its initial state. During a complete screwing sequence, all related activities of the transfer-loading station are interrupted; the bringing a new empty recipient on the main conveyor and the evacuation of a filled cap screwed vessel are subsequent sequences, which are performed only after stations 2 and 3 corresponding operations were finished.

III. Achievement of the Petri Net Model

The bottling station is a modular structure which contains – in each of its subsystems - electro-pneumatic drive devices. Each of six main drive modules consists of a double-acting cylinder (actuator) and a directional discrete control valve. Because most of devices of electro-pneumatic automation (cylinders, directional control valves, pressure valves etc.) works in a finite number of states reachable starting an initial state at the occurrence of external events, the model achieved by the authors for representation of an operational scenario was a non-autonomous PN (P – temporized or T temporized).

A. Review on discrete Petri Nets

Petri Nets, known initially as an analysis tool of discrete event drive systems gained – through subsequently developments of their own formalism - unique strength in hybrid systems representation and in study of qualitative and quantitative their properties. Hence, Petri Nets is a powerful tool in the modeling of hybrid systems with autonomous commutation of the model generated by a hysteresis phenomenon through a particular Petri Nets structures, called Modified Petri Nets (MPN). They are a formal description language for such hybrid systems, which combines the advantages of a graphical description with the possibility of a transparent visualization, simulation and analysis [5], [6], [8], [9], [12].

The PN have two important characteristics. First due to own graphical representations they allow the modeling of various behavioral scenarios commonly found in discrete event dive systems dynamic as the parallelism, the concurrency, the resources sharing etc. Then, the achieved models can be analyzed qualitatively (as autonomous models) and then quantitatively, by addition of time at the places or at the transitions of autonomous PN model. We can associate a timing with the duration of an operation or with an expected time before some event occurrence such as a failure for example. Constant timings and stochastic timings with exponential distribution are commonly used models since the allow performance evaluation thanks to analytical methods [6], [14].

Briefly, a PN is a bipartite graph, with two types of nodes: places (positions) and transitions. Oriented arc connects the places to the transition or vice-versa: the transitions to the places. It is not allowed the connection between two nodes of the same type (places-places or transitions – transitions). Usually, the places are represented as circles and the transitions as vertical or horizontal bars. Each place can contains one or many tokens (graphically represented as points), which indicates the states (the whole dynamic) of the PN (Fig. 2).

Through a mathematical formalism, a PN is an quintuple PN = (P, T, A, W, $\mathbf{M}_0$), with $P = \{P_1, P_2, \ldots, P_n\}$ a finite set of places, $T = \{T_1, T_2, \ldots, T_q\}$ - a finite set of transitions, $A \subseteq (P\times T) \cup (T\times P)$ the finite set of arcs, $W : A \rightarrow \{1, 2, \ldots\}$ – the weight of arcs and $\mathbf{M}_0 : P \rightarrow \{0, 1, 2, \ldots\}$ the initial marking (initial state) of the PN. For this type of PN, one of the main methods used for qualitative analysis is the construction of the reachable tree of the model, which allows finding the most usual of behavioral properties of the PN.

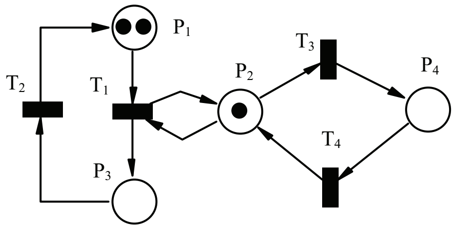

Fig. 2. Discrete Petri Net example.

More than that, the temporized PN is very well suited for the analysis of quantitative properties of the modeled system. However, when the system modeled reaches a great number of states, the analysis of the model is always made by online simulation, using various software tools [5], [6], [7], [9], [10].

B. Some PN models of electro-pneumatic drives

To achieve the whole model of bottling station, several sub-models of electro-pneumatic drives were interconnected. Usually, a pneumatic circuit contains a directional control valve which when is turned on switches and commands the forward stroke of an actuator with single or double action. Directional control valves are commutation devices operating in pneumatic power circuits. Generally, they are used in addition with single or double acting cylinders, for its command.

The model of a directional control valve is a synchronized PN (Fig.3): their places represent suitable conditions for states evolution and its transitions are fired at the occurrence of external events (sensors outputs and external command signals), [11], [12].

Each of pneumatic actuators can be represented as a discrete synchronized PN (Fig.4.) in which: P_1 denotes the initial state of the actuator (S_1 = 1), P_2 denotes the forward stroke until S_2 is activated, P_3 shown the extreme position of the actuator and finally, P_4 denotes his come-back stroke.

The start of forward movement is given by the firing of transition T_1, after its directional control valve has been turned on; then, after activating the sensor S_2 (end of stroke) transition T_2 is fired and P_3 in marked with one token and so on, until the entire forward – return cycle was done.

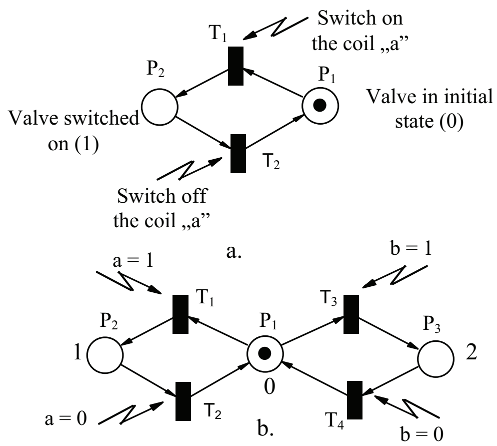

Fig. 3. PN models of directional control valves :
a) with 2 states ; b) with 3 states.

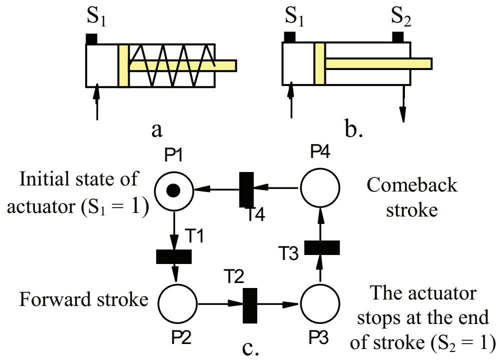

Fig. 4. Explanatory for the actuator PN model:
a) single acting actuator; b) double acting actuator;
c) The PN proposed model.

Based from the above sub-models, the pneumatic actuator with its directional control valve can be represented also as a synchronized PN (Fig.5.).

The synchronisation between the PN transitions were indicates by test arcs (dotted-line represented). Hence, one output transition of a test arc will be fired only the marking of its source place becomes greater or equal with the weight of the arc connecting them (Fig.5.). The test arcs do not realize tokens transportation between the places of the PN through the transitions connected by this [9], [10], [12], [13].

First, transition T_1 is fired thanks to the non-null marking of the P_7 (the actuator is in initial state). So, the directional control valve switches on, the P_2 token moves in P_1 and validates transition T_5, which will be fired. The actuator moves on (one token in P_4) and so on.

C. *The Object Net paradigm*

The most mathematical, textual or graphical approaches to describe real systems are currently usable for small examples, but models of complex systems are unwieldy. Therefore a hierarchical concept to structure a model is needed. In order to solve the mentioned handling problems arising from the system complexity, some authors [10], [11] proposed an object oriented paradigm for the analysis of the models with reduced effort. One of the important advantages of using this concept is the ability to describe larger systems by their decomposition into interacting objects.

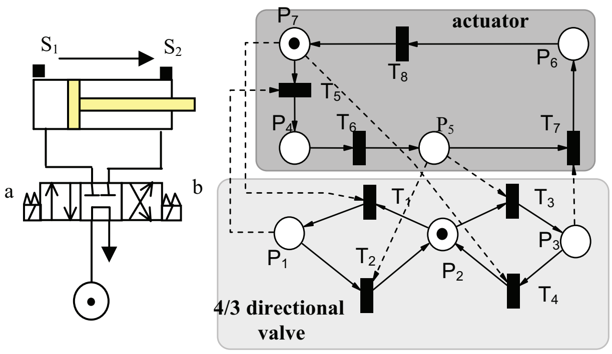

Fig. 5. PN model of sub-system actuator, 3 states directional control valve.

Because of the objects properties, changing of the system model could be easier achieved. The object-oriented concept combines the advantages of the modules and hierarchies and adds useful new concepts (inheritance, reuse, encapsulation, information hiding, data exchange etc.) [8], [9], [10], [12], [13], [19].

More often, the attributes are represented at the model by its places with their markings. Information hiding is realized by encapsulation the detail topology of the net and by publishing selected places, using an interface. Then, inheritance is the next step from a class to an abstract object. If an object will be abstracted from a class, it inherits the whole net structure, including the interface and data exchange is given by the token flow between the objects. Those may be refined by adding places, transitions, arcs and objects. Thus, every object is represented as a hierarchical structure, which contains three layers (Fig.6). In the lowest layer, the parent net is represented. In the middle layer, the net inherited by the class is enclosed in an object frame. In this layer, various net elements and objects can be added, in order to modify the behaviour of the object. In the top layer, we get the object frame, which encapsulates the inner net structure of the object

D. *PN model of the bottlig station*

The whole PN model was synthesized through a bottom-up technique by aggregation of its sub models (Fig.7)

In fact, the model can be considered as an interpreted and extended PN, which operates at the occurrence of external events associated to model transitions, if some condition is satisfied, when some event occurs. Moreover, to evaluate the performances of the system modeled, T-timed transitions were used.

All the models were realized using the Visual Object Net ++ tool and theirs behavioral properties (boundedness, liveness, deadlocks) have been verified by on-line certain simulation scenarios [8], [9], [10], [11], [12] (Fig8).

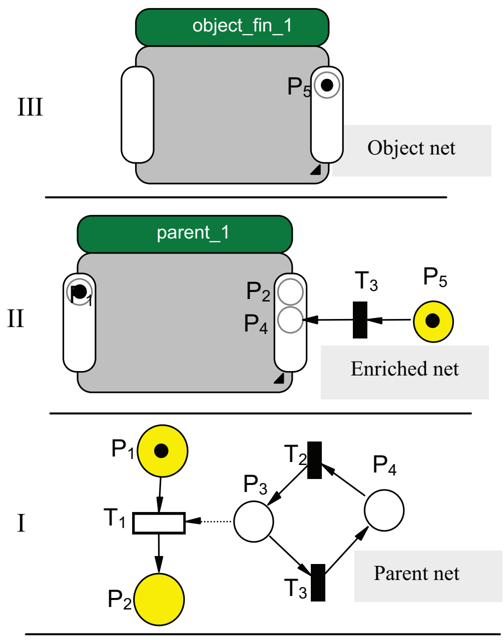

Fig. 6. Hierarchical structure.

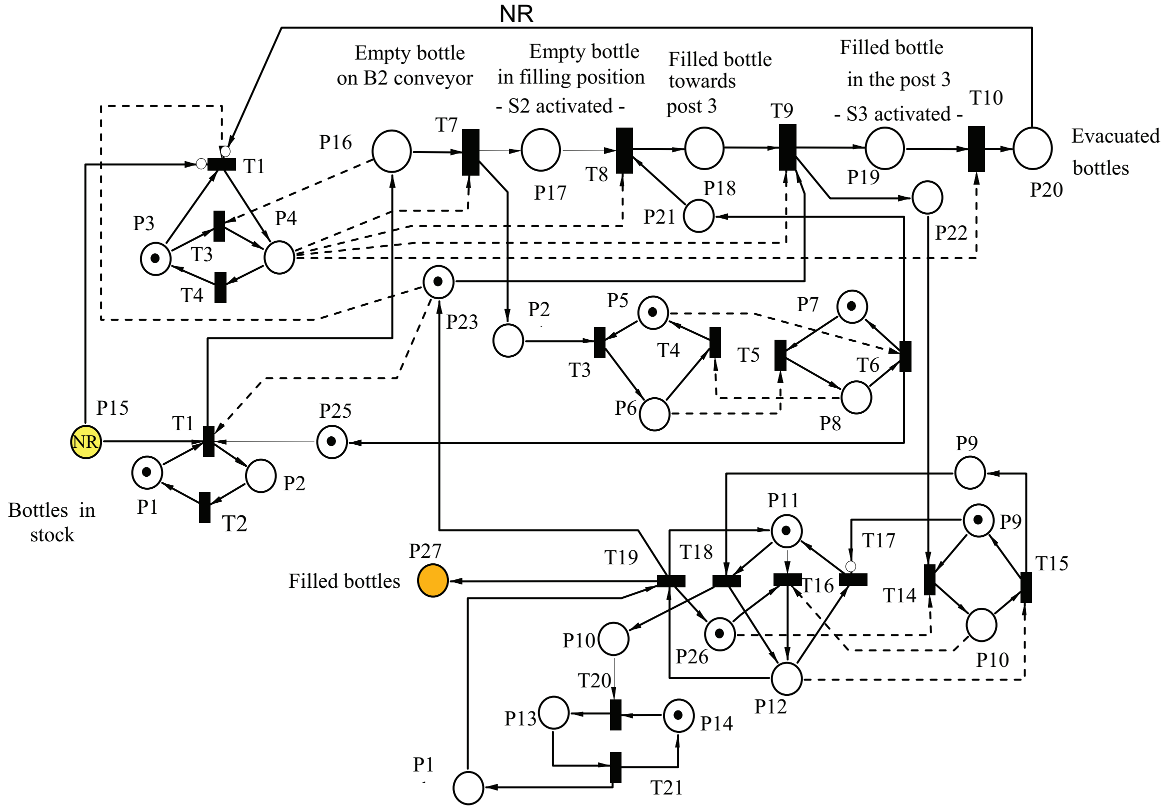

Fig.7. The Petri Net model of the bottling system.

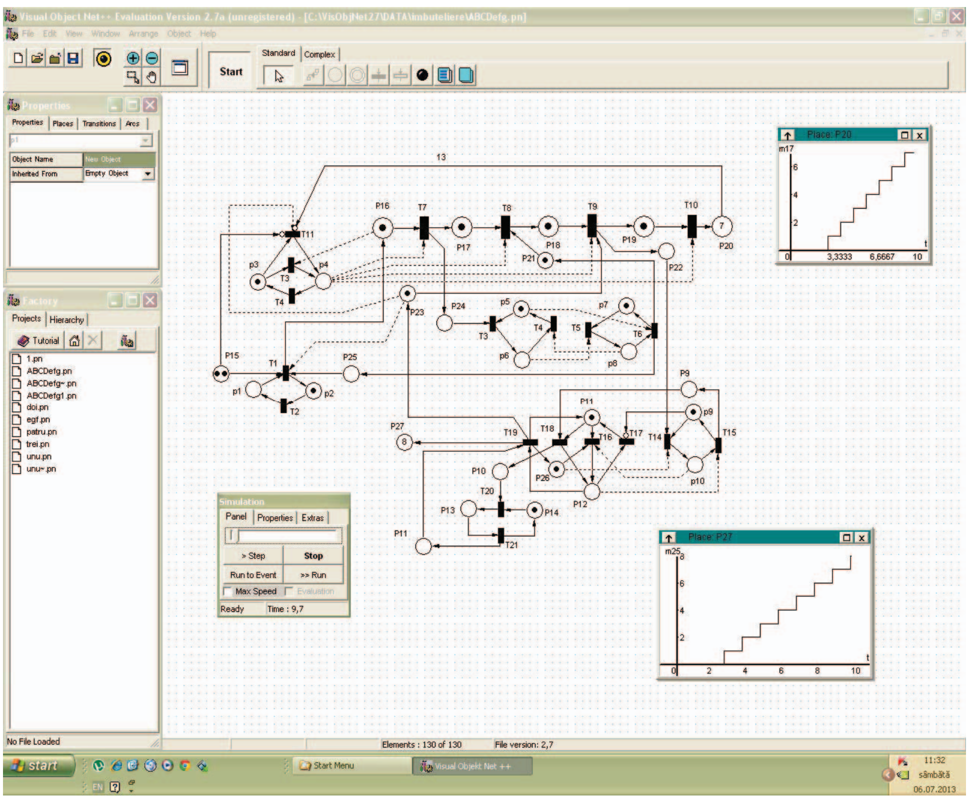

Fig.8. The main window of Visual Object Net++ tool.

IV. Conclusions

The purpose of this paper was to describe the dynamic of a water bottling line in an operate scenario as that of a discrete event drive system and to synthesize its PN model. At the beginning, an autonomous PN was achieved whose the behavioral properties have been analyzed, them in addition of delays to the transitions, it has been transformed in an T-timed PN model. Taking into account the operating mode of system modeled, the PN model was extended, becoming an interpreted generalized discrete PN. However, the bottling plant may be considered as a hybrid structure, with discrete and continuous subsystems which interacts, reaching a great number of states in its evolution. Moreover, a hybrid system is composed of digital and continuous devices, in which digital control programs controls and supervise continuous and discrete plants. In the meantime, the bottling process may be considered like a batch process, where the material is operated by finite quantities (the batches); at any time, an integer number of batches are in operation at many locations in the plant. In this way, the process looks like a discrete manufacturing system.

A mathematical model of such a process has thus to be a hybrid model involving discrete variables (integers or with a domain in a finite set) and continuous variables (real numbers). Both dynamics (discrete and continuous) have to be modeled: a discrete event based dynamics for discrete variables (sequence of operations) and a continuous time dynamics for continuous variables (differential algebraic equations). The general approaches have strong similarities with hybrid automata, but the discrete dynamics is represented by Hybrid Petri Nets in place of automata in order to address in an explicit way resource allocation policies.

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