Trend of Scientific Research: Analysis of Mega-Data of Discrete Event Systems Described by Petri Nets and Their Extensions

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Abstract: In this article, we are interested in the discrete event systems modeled by Petri nets and their extensions and we analyze the mega-data of more than one thousand articles published in the last forty years to determine the trend of the scientific research in this domain.

Key words—discrete event systems, Petri nets, trend of the scientific research.

I. Introduction

Discrete event systems are dynamic systems whose state space is discrete and whose evolution is consistent with the occurrence of physical events to potentially irregular or unknown intervals. These systems are increasingly present in many sectors, such as the automotive industry, manufacturing systems, telecommunications, aeronautical, etc.

The class of discrete event systems has been widely studied in the literature [1-4]. Its interest is justified by the existence of a large number of real systems evolve to the occurrence of events. The ambiguity lies in the choice of the most appropriate tool to describe these systems. The tool we are dealing with is Petri nets that have multiple extensions [5-10].

Given the diversity and multitude of extensions of Petri nets, researchers are faced with the confusion of choosing the most appropriate tool. The present work aims to build a mega-data base by the treatment of more than one thousand articles dealing with discrete event systems described by Petri nets in the last four decades, in order to determine the tool that constitute an active, open and scalable axis of scientific research.

This article is going to focus only on Petri nets and their extensions. Other tools (Automata and Mathematical tools) are the subject of [11, 12].

This paper is organized as follows: In the second section, we recall the different notions on discrete event systems and some definitions of key words used along this paper. The third part is devoted to the problematic and the methodology used for the classification of articles. The fourth section represents discussions of the results obtained and the last one concludes the paper.

II. Terminologies

This section presents some important reminders terminologies in the field of discrete event systems. The objective of this section is not to propose new terminologies, but to implement all the definitions of terms used in this article.

1. Discrete event system

A discrete event system (DES) is a dynamic system that evolves in accordance with the abrupt occurrence, at possibly unknown irregular intervals, of physical events. Such systems arise in a variety of contexts ranging from computer operating systems to the control of complex multimode processes.[13]

2. Decision-making structures

2.1. Centralized structure

The centralized approach is an approach where there is a single module of analysis or decision (supervisor or diagnostician) which collects and analyzes global information coming from the process.

2.2. Decentralized structure

The decentralized approach is an approach where there are several elementary decision-making structures of the same type. Each one of these structures collects a part of the global information. The global decision is obtained by performing a functional calculus on all decisions of the elementary structures.

3. Types of discrete events systems

3.1. Deterministic system

A deterministic system is a system which always reacts in the same way to an event. The system state is described by a well-defined process, that is to say, regardless of what happened before, from the time the system reaches a given state, its evolution will always identical. [14]

3.2. Non-deterministic system

As opposed to a deterministic system, a system is non-deterministic if one or more of its output variables are random variables. A probabilistic framework is required for the study of these systems.

4. Petri nets and their extensions

Petri nets: A Petri net $N = (P, T, A, W, M_0)$ is a bipartite graph, where $P = \{p_1, p_2, ..., p_n\}$ is the set of places, $T = \{t_1, t_2, ..., t_m\}$ is the set of transitions, $A \subseteq (P \times T) \cup (T \times P)$ is the set of arcs, $W: A \rightarrow \{0, 1, 2, ...\}$ is the arc weight function, and for each $p \in P$, $M_0(p)$ is the initial number of tokens in place p.

The notation •p denotes the set of input transitions of place p: $\bullet p = \{t | (t, p) \in A\}$. Similarly, p• denotes the set of output transitions of p. The sets of input and output places of a transition t are similarly defined by •t and t•.

A transition t in a Petri net is enabled if every input place p in •t has at least W (p, t) tokens in it. When an enabled transition t

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fires, it removes W (p, t) tokens from every input place p of t, and adds W (t, p) tokens to every output place p in t•. By convention, W (p, t) = 0 when there is no arc from place p to transition t. When W (a) = 1, ∀a ∈ A, Petri nets are called ordinary. [15]

Timed Petri nets: A timed Petri net is a six-tuple N = (P, T, A, W, M_0, f) where:

- (P, T, A, W, M_0) is a marked Petri net,
- f: T → R+ is a firing time function that assigns a positive real number to each transition on the net.

Therefore, the firing rule has to be modified in order to consider time elapses in the transition firing. If an enabled transition t_j ∈ enb (M) then it will fire after f (tj) time's units since it became enabled. The system state is not only determined by the net marking but also by a timer attached to every enabled transition in the net. [16]

Time Petri nets: A time Petri net is a six-tuple N = (P, T, A, W, M_0, I) where:

- (P, T, A, W, M_0) is a marked Petri net,
- I: T → {R+, R+ ∪ {∞}} associates with each transition t an interval [↓ I(t), ↑ I(t)] called its static firing interval. The bounds of the time interval are also known as EFT and LFT respectively.

The enabling condition remains the same as in the timed Petri Net but the firing rule must be redefined. The possibility to fire in a time interval rather than an exact time lead to the existence of infinite clock states. [16]

Stochastic Petri nets: A stochastic Petri net is a six-tuple SPN = (P, T, A, W, M_0, Λ) where:

- (P, T, A, W, M_0) is a marked Petri net,
- Λ is the array of firing rates λ associated with the transitions. The firing rate, a random variable, can also be a function λ (M) of the current marking. [17]

Colored Petri nets: Colored Petri nets (CPN) have different characteristics from other classes, where token(s) and places are attached with a color identifying the type of that token and place.

A Colored Petri Net is a tuple CPN = (Σ, P, T, A, τ, G, E, I) where:

- Σ is a finite set of non-empty types, called color sets.
- P is a finite set of places.
- T is a finite set of transitions with P ∩ T = Ø
- A is a finite set of arcs such that A ⊆(P x T) ∪ (T x P) and A ∩ (P ∪T) = Ø
- τ is a color function, τ: P → Σ ; where τ (p) = C* for p ∈P and C* ∈ Σ
- G is a guard function, G: T → expr ; where:

t ∈T: [Type (G(t)) = bool Λ Type (Var(G(t))) ⊆ (Σ].

- E is an arc expression function, E: P x T∪T x P → expr; where:

E(x1,x2) = Ø if (x1,x2) /∈ A and a ∈ A: [Type(E(a)) = τ (p(a)) Λ Type(Var(E(a))) ⊆ Σ] ; where p(a) is the place of arc a.

- I is an initialization function, I: P → expr ; where:

I(p) is a closed expression (i.e. it contains no free variables) and p ∈P: [Type(I(p)) = τ (p)].

Notes:

(a) If a place holds tokens of color type C, then its multiset type C* ∈ Σ.

(b) Places serve to hold tokens, with the distribution of tokens determining the state of the net.

(c) Transitions serve to effect changes of state, and hence are distinct from places. [18]

5. Decision support tools

Control: The function that triggers the execution of a set of operations by giving orders to the process actuators, which may be:

- A set of operations corresponding to the manufacturing sequence of the product.
- A set of operations executed in order to restore the process functionality offered during normal execution.
- Actions with a high priority level applied in order to protect the shop workers and to prevent catastrophic developments.
- Some checking, tuning or cleaning operations executed in order to maintain the process in an operational state.[19]

Supervision: The function that computes and sets the parameters of the control sequence to be executed according to the state of the control system and to the state of the process. This includes normal and abnormal operations. During normal operation, supervision takes the decisions to raise the indecision in the control system (real-time scheduling, optimization, control sets and switching from one control law to another). When a process failure occurs, supervision takes all the decisions necessary to allow the system to resume normal operation (rescheduling, recovery actions, emergency procedures, etc.). [19]

Monitoring: The function that collects data from the process and from the controller determines the actual state of the controlled system and makes the inferences needed to produce additional data (historic, diagnosis, etc.). Monitoring is limited to data processing and has no direct action on the models or on the process. [19]

Diagnosis: The function that looks for a causality link between the observed symptom, the failure and its origin. Classically, three sub-functions are distinguished:

- Localization determines the subsystem responsible for the failure,
- Identification identifies the causes of the failure,
- Explanation justifies the conclusions. [19]

Simulation: Simulation is the activation of the model over time, in order to know its dynamic behavior and predict future behavior.

The simulation is mainly used to study the physical flows (parts, materials, tools, etc. ...) and data-processing (manufacturing orders, Kanban, etc. ...) in the workshop and the availability of resources (operators, machines, etc.) [20]

Modeling: Modeling of a physical system is a description of its structure and a behavioral or functional representation of each of its components.

A behavioral representation is established by relations between the different variables of the system, typically called relations of cause to effect. A functional representation is more abstract because it addresses only the presumed objectives which the physical system has to fill. [21]

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III. METHODOLOGY

Discrete event systems are a scalable axis of research and they have received much attention over the last four decades. The presence of multiple extensions of Petri nets for modeling these systems generates an enormous diversity of research areas and sets the new researchers in confusion to choose the most suitable axis to develop.

In this paper, we propose the analysis of the mega-data base which allows the classification of over than one thousand articles dealing with discrete event systems described by Petri nets and their extensions. The establishment of this database will allow future researchers to easily start their research through:

- Statistical processing of previous publications,
- Following up the development of this discipline,
- Evaluation of the level of maturity of each tool.

The treated articles are classified as follows:

- The structure of decision making (centralized, decentralized).
- The type of system studied (deterministic, non-deterministic).
- The decision-support tool (control, supervision, monitoring, diagnosis, simulation, modeling).

After the classification, we traced the curves representing the number of articles based on their publication years. The interpretation of these curves is based on their shapes. Figure 1 summarizes all possible interpretations.

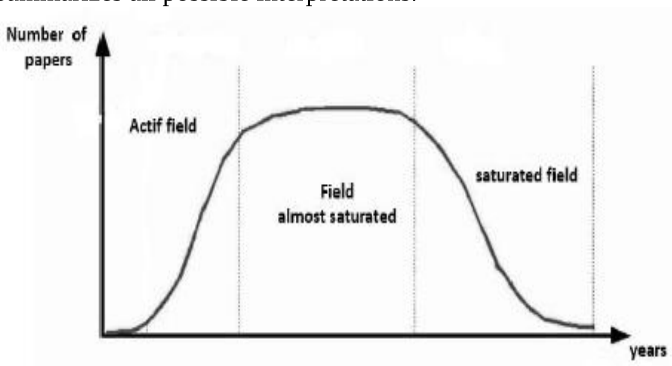

Figure 1: Interpretation of curves

IV. RESULTS AND DISCUSSION

The importance of discrete event systems has led researchers to discover and develop several modeling tools. Among these tools we will focus on Petri nets that are increasingly used in the literature.

Figure 2 shows the appearance of the most used extensions of Petri nets that constitute the trend of research in the field of discrete event systems: Discrete, timed and time, colored and stochastic Petri nets.

Fuzzy, lots, interpreted and oriented object Petri nets and other types of Petri nets are not less important but less used compared to the previous type.

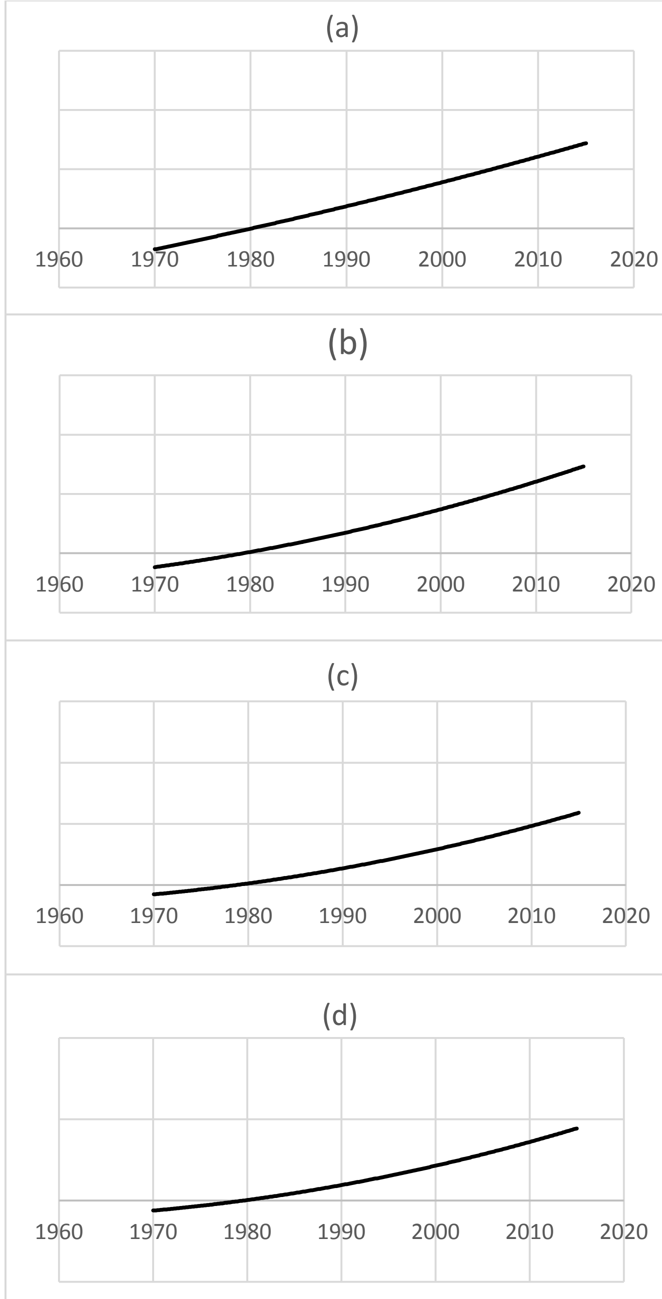

Figure 2: (a) Discrete, (b) Time and Timed, (c) Colored and (d) Stochastic Petri Nets

1st Result: As already mentioned, these graphs represent just four types of Petri nets that are treated in a very large number of articles.

1. Discrete Petri nets

1.1. Deterministic system

Discrete Petri nets are a very appropriate tool for the study of deterministic systems. Figure 3 shows the number of articles dealing with discrete Petri nets in deterministic systems based on years of publication.

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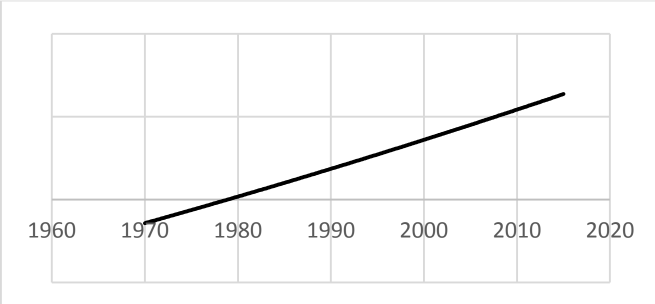
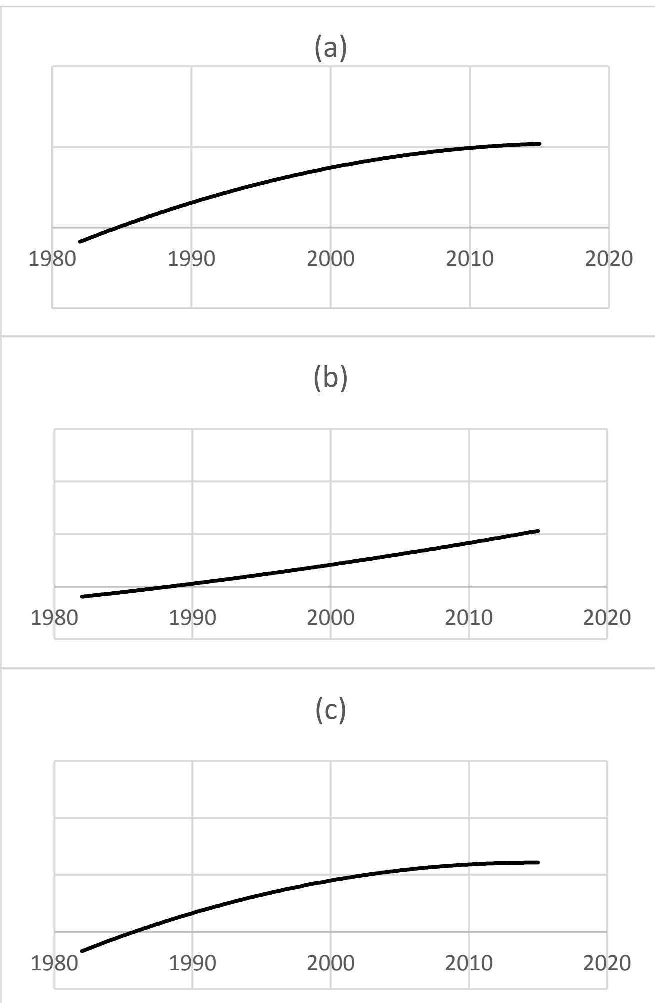


Figure 3: Trend of research: Discrete Petri nets for deterministic systems

The use of discrete Petri nets to describe deterministic systems has steadily increased since the eighties until now.

To target the usefulness of this type of Petri nets for deterministic systems, we plotted graphs (Figure 4) which represent a variation of the number of articles dealing with the modeling, the supervision, the simulation and the control of deterministic systems by discrete Petri nets.



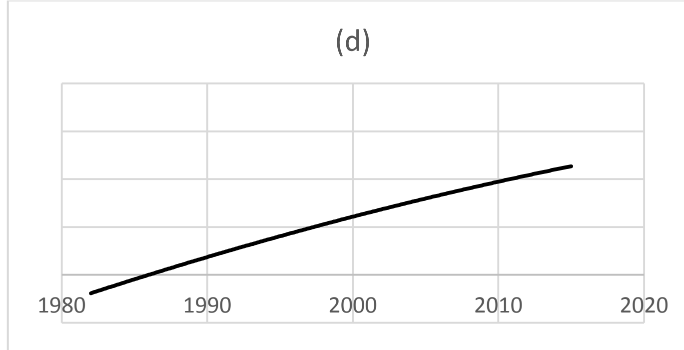


Figure 4: (a) Modeling, (b) Supervision, (c) Control and (d) simulation of deterministic systems by discrete Petri nets

2nd Result: The trend of scientific research for the control of deterministic discrete event systems by discrete Petri nets begin to saturate, on the other hand the modeling, the supervision and the simulation of these systems by discrete Petri nets are very active research areas.

1.2. Non deterministic system

As for deterministic systems, discrete Petri nets are always used for the non-deterministic systems. Figure 5 shows the number of articles treating discrete Petri nets with non-deterministic systems based on years of publication.

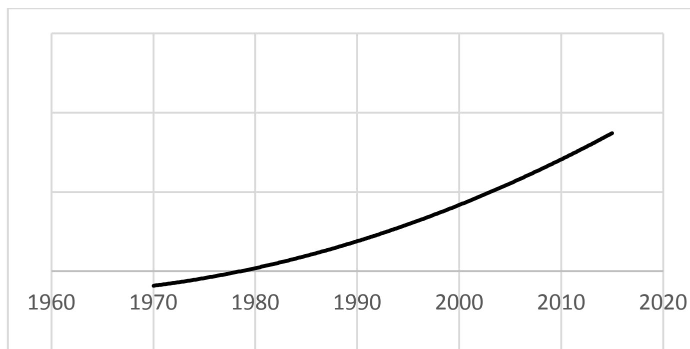
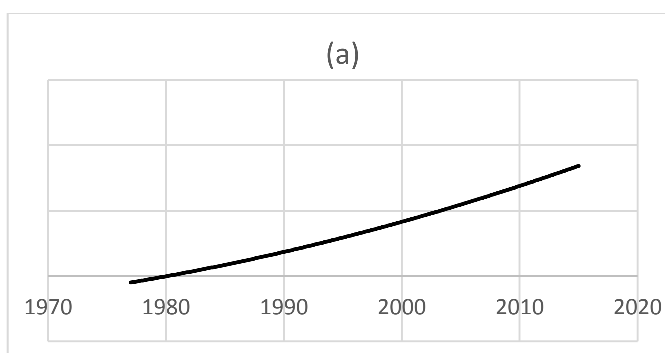


Figure 5: Trend of research: Discrete Petri nets for non-deterministic systems

The following step is plotting graphs (figure 6) representing the variation in the number of articles dealing with modeling, supervision, simulation and monitoring of non- deterministic systems by discrete Petri nets.



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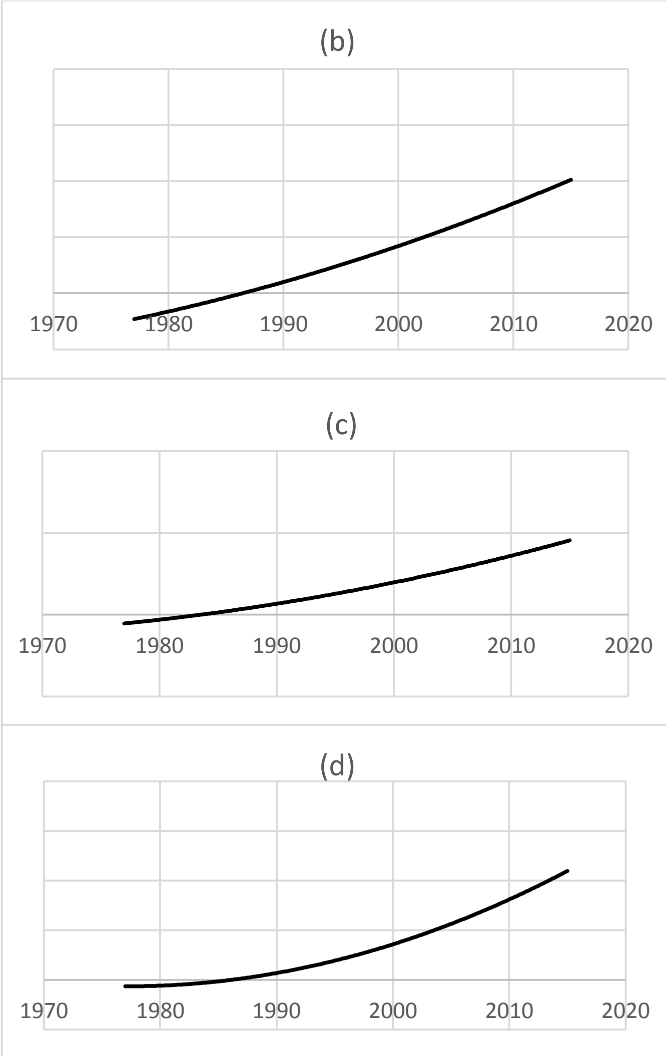


Figure 6: (a) Modeling, (b) Supervision, (c) simulation and (d) Monitoring of non-deterministic systems by discrete Petri nets

3rd Result: Modeling, supervision, simulation and monitoring of non deterministic systems by discrete Petri nets represent active areas of scientific research.

1.3. **Centralized structure**

The description of discrete event systems in centralized structures with discrete Petri nets is very little used by researchers; this can be explained by the boundary of the tool to describe this structure. (figure 7).

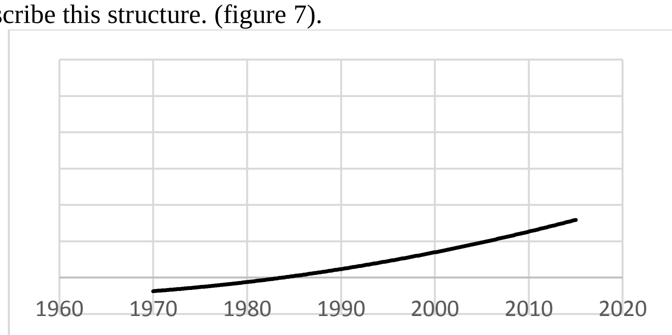


Figure 7: Trend of research: Discrete Petri nets for centralized architecture

4th Result: The use of discrete Petri nets in centralized structures weakly increases and tends towards saturation.

1.4. Decentralized structure

The use of discrete Petri nets in decentralized structures is growing; figure 8 represents the number of articles treating discrete event systems in decentralized structures by discrete Petri nets.

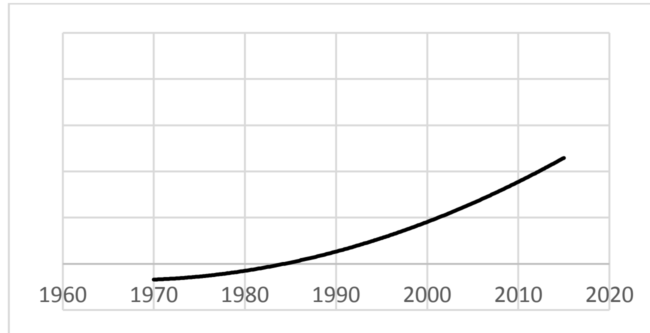


Figure 8: Trend of research: Discrete Petri nets for decentralized architecture

5th Result: The description of discrete event systems in decentralized structures by discrete Petri nets is considered a center of attention of researchers.

2. Time and timed Petri nets

In this section, we consider the Timed Petri nets and Time Petri nets because they represent the same concept that is the consideration of the time. The discrete event systems described by these tools are deterministic systems having a centralized structure. The study of discrete event systems by Petri nets knew a growth very accelerated during the last twenty years (figure 2). The number of articles, based on years of publication, representing the modeling and control of these systems by timed and time Petri nets are shown in figure 9.

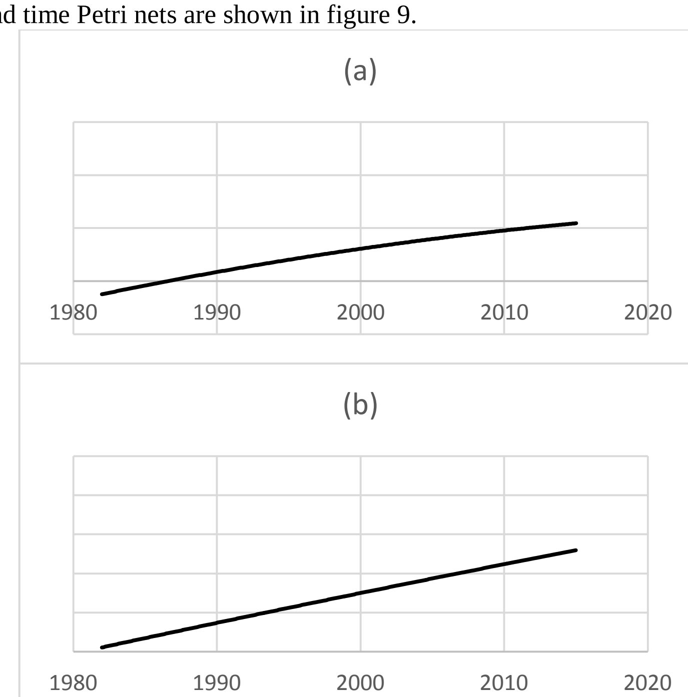


Figure 91: (a) Modeling and (b) Control of deterministic discrete event systems by time and timed Petri net

6th Result: Modeling and control of discrete event systems by deterministic timed and time Petri nets are two research areas that are very active. Scientific researchers are interested more and more in these areas seen the interest of Petri nets by the concept of time.

3. Colored Petri nets

Colored Petri nets are not highly cited relative to discrete Petri nets and timed Petri nets.

We traced the change of the number of articles, based on years of publication, processing this tool for modeling and control of deterministic discrete event systems (figure 10).

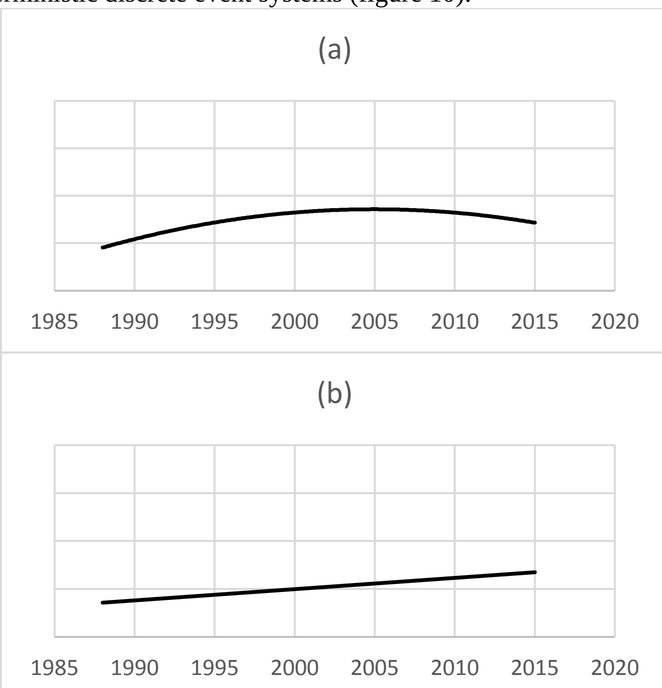
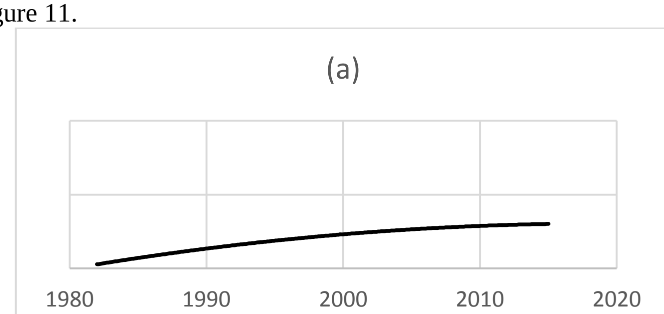


Figure 10: (a) Modeling and (b) Control of deterministic discrete event systems by colored Petri net

7th Result: On average, there are one to two articles published each year for modeling and control of discrete event systems by colored Petri nets. This can be considered as a motivation for researchers to further develop this tool.

4. Stochastic Petri nets

Non-deterministic discrete event systems are often modeled by stochastic Petri nets. Modeling, control and simulation of such systems by these Petri nets were the subject of several articles published in the last twenty five years. The result is shown in figure 11.



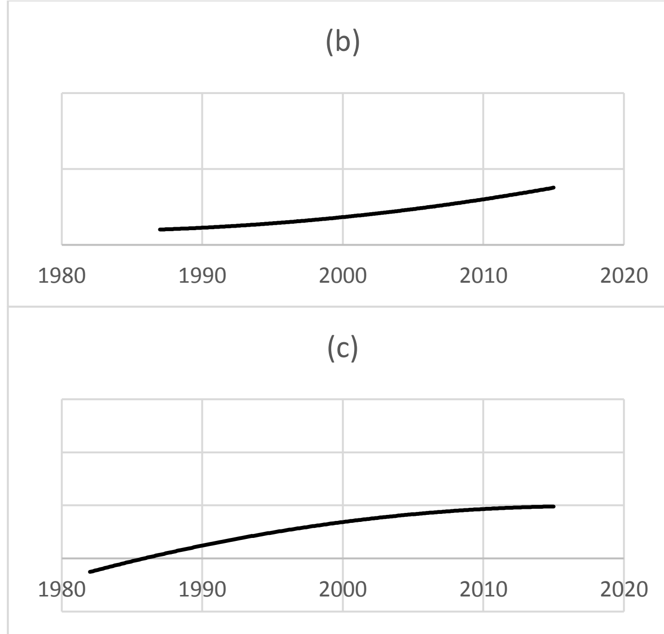


Figure 11: (a) Modeling, (b) Control and (c) simulation of deterministic discrete event systems by stochastic Petri net

8th Result: Stochastic Petri nets are considered a very appropriate tool for describing nondeterministic discrete event systems. Simulation and control of these systems by this type of Petri nets are areas that attracted the attention of researchers in recent years.

V. CONCLUSION

The objective of this study was to evaluate the trends of scientific research of discrete event systems described by Petri nets and their extensions. We were able to determine from over one thousand articles published during the past forty years, the axes of the most active research:

- Discrete Petri nets in deterministic systems (Control, supervision and simulation).
- Discrete Petri nets in non-deterministic systems (Modeling, supervision, simulation and monitoring).
- Time and timed Petri nets (Modeling and control).
- Colored Petri nets (Modeling and control).
- Stochastic Petri nets in non-deterministic systems (Simulation and control).

This work can extend in several ways; it will guide and help researchers to choose the appropriate tool to describe discrete event systems according to the desired objective.

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