Applications of Petri nets Based Models in Manufacturing Systems: A Review

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Abstract

Petri nets are a powerful graphical tool for modeling, analyzing, and control concurrent, parallel, simultaneous, synchronous, distributed, and resource sharing manufacturing systems and are widely used today. In this paper, a comprehensive overview for applications of Petri nets and their extensions in modeling, analyzing, and control of manufacturing systems are presented. More than 25 major production, manufacturing, operations management, and control journals published in years 1988–2015 has been reviewed. The survey is classified into two fields, applications Petri nets with modeling and analyzing and applications Petri nets with control, each field is classified into three groups, and additionally a historical progression in these fields was emphasized. This work offers readers updated results in this area and makes it easier on engineers in finding a convenient principle or technique for their industrial scenarios. Finally, recommendations for future research trends are introduced in this paper.

Keywords

Petri nets, modeling, control, automated manufacturing system, review

1 Introduction

Manufacturers must adapt to changes in the production environment as well as in the market in order to achieve and maintain competitiveness. Effectively designing and operating an automated manufacturing system (AMS) is important for manufacturers to reach this goal. An AMS conglomerates of machine tools, robots, buffers, fixtures, automated guided vehicles (AGVs), and other material-handling devices. Different types of parts enter the system at discrete points of time and are processed concurrently; these parts cause a high degree of resource sharing.

It is a difficult to predict the behaviour of manufacturing systems without modelling, analyzing, and control techniques. Therefore, several techniques have been developed to describe the behaviour of manufacturing systems. One of which are Petri nets (PNs). Petri nets are a powerful graphical tool for modeling and analyzing concurrent, parallel, simultaneous, synchronous, distributed, and resource sharing systems. There are many advantages of using Petri nets such as enable an easy visualization of complex systems, can model a system hierarchically (a top-down fashion at various levels of abstraction and detail), and can analyze qualitative and quantitative aspects of the system, qualitative analysis searches for structural properties like the absence of deadlocks, the absence of overflows or the presence of certain mutual exclusions in case of resource sharing. Quantitative analysis looks for performance properties such as throughput, utilization rates, average queue lengths, or average completion times. The objective of this paper is to introduce a comprehensive review of works on various PNs applications proposed for the modeling, analyzing, and control of manufacturing systems. Moreover, it offers readers updated results in this area and makes it easier on engineers in finding a convenient principle or technique for their industrial scenarios. Including this introductory section, the paper is organized as follows. Section 2 provide the basics of Petri net. Sections 3 reviews and discusses the literature of PNs applications for the modeling, analyzing, and control of manufacturing systems. Finally, in section 4, the paper is concluded and the future research directions are indicated.

2 Petri net structure

Petri net theory was originally developed by (Petri 1962) and presented in his his Ph.D. The common definition of PNs introduced by Petri is as follows. A Petri net or place/transition net can be defined as a five-tuple;

$$PN = (P, T, I, O, Mo) \quad (1)$$

Where, P and T are a finite non-empty sets of places pictured by circles and transitions pictured by bars, respectively. I: P x T→{0, 1) is an input function that defines the set of directed arcs from P to T. O: P x T→{0, 1) is an output function that defines the set of directed arcs from T to P. Mo: P → N, is a marking whose i^{th} component represents the number of tokens in the i^{th} place Pi. P and T are disjoint sets, and $P \cup T$ are called nodes with $P \cup T \neq \emptyset$ and $P \cap T = \emptyset$. The Petri nets are assumed to be connected; it means that there is at least one path between any two nodes. More obvious, the input and output functions of Petri net can be represented by arcs with arrows between two different types of nodes. The initial marking of the net is denoted by Mo, which represents the different raw parts that are to be synchronously processed in the system, and the state of resources, such as machines and robots. A marked PN and its elements are shown in Figure 1. In generally, places are used to represent the resource status, operations, and conditions, the transitions are used to express the control evolutions from one state to another, processes, activities, and events, directed arcs correspond to flow the material, resource, information, and control flow direction between states, while tokens are used to represent the material, information, and resource. Note that in a Petri net model the transitions may be immediate or timed, and conflict or in concurrent. When a token is located in a place, the place is said to be "enabled". When a token flows from one place to another, the process is referred to as "firing". Immediate transitions fire as soon as they are enabled. In timed transitions, there is a delay between enabling and firing. A timed transition is used to represent the start and end of system activities. A timed transition may be deterministic time or exponential, fuzzy, uniform, or any discrete and continuous probability distributions. The behaviour of the system is described in terms of the system states and their changes. In a PN model, the system state is defined as a marking. The new system state appears when the transition fires.

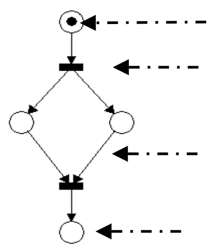

Figure 1: A simple Petri net

3 Applications of Petri nets in Manufacturing Systems

3.1 PNs with modeling and performance analysis

In this section, some of the most important studies in modeling and performance analysis using Petri nets are presented. This section can be classified into three groups, deterministic timed, stochastic timed, and fuzzy timed Petri nets.

3.1.1 Deterministic Timed Petri Nets

The study in (Zhou et al. 1993) is considered to be seminal research and earlier that presents the use of deterministic timed Petri nets in modeling and analyzing of a real life a flexible manufacturing system. More importantly, top-down refinement, modular composition, and system decomposition ideas are used to achieve boundedness, reversibility, and liveness of the system model that ensure the system can be operated in a stable, deadlock-free, and cyclic manner. A new paradigm, called colored timed object-oriented Petri net (CTOPN) is proposed by (Wang and Wu 1998). The proposed paradigm owns the characteristics of colored Petri net (CPN), timed Petri net (TPN), and object-oriented Petri net (OPN). A CTOPN model consists of four major characteristics: (1) the dynamics behavior of an FMS are represented by an OPN, (2) the characteristics of material flow and processing time in an FMS are represented by the input/output transform functions, colored tokens and the associated time-delay attributes, (3) the dynamic behavior/control logic of an AMS can be clearly analyzed, (4) simultaneously, modeling, analyzing, scheduling and controlling of an AMS are provided. Different from the traditional modeling method for automated guided vehicle (AGV) in an automated FMS. The work in (Tiwari et al. 2001) has attempted to model AGV by using deterministic timed petri net and Activity Cycle Diagrams (ACDs). A deterministic timed petri net is used for planning of AGV system in FMSs that guarantees deadlock free and conflict-free operations of the system. ACD is used to simulate the entities behaviour. Under such a modeling paradigm, mean utilization and the utilization index have been taken as performance measures to evaluate the system.

Modeling together, the production plans for several products and the structure of the FMS are a major issue. In order to tackle this issue, Aguiar et al. (2008) proposed systematic procedure for modeling, analyzing, and simulating a FMS using deterministic timed colored Petri nets (deterministic timed CPN). The proposed method implies a systematized sequence to construct such models, which are an approach to convert a normal Petri net into a colored Petri net, a library of colored Petri net valid subnets for industrial systems and an extension of Mutual Exclusion Parallel (PME) and Serial Mutual Exclusion (SME) theories for modeling of shared resources in FMS. It is shown that this method reduces the number of graphic elements comparing with if production plans and structure are modelled separately. However, it is necessary to make performance measure of different model variants in two cases to ensure the proposed method is effective. The work in (Coman et al. 2009) uses deterministic timed Petri nets to model, simulate, and evaluate of a simple manufacturing system. The system consists of two identical machines and a robot (R). The system Petri net model has achieved in Petri Net Toolbox under MATLAB environment. The simulation of system provides the system's behaviour, average manufacturing time, and utilization of system resources. Reconfigurable manufacturing systems (RMSs) have been provided the manufacturing companies with the desired production capabilities and capacities. This can be achieved via reconfiguring system components for a variety set of products which may require short delivery lead times and small quantities. As a result, Zhang and Rodrigues (2009) proposed a new formalism to model RMSs with coloured timed PNs, which considers production variation, variety handling, and machine selection through the process of reconfiguring system elements. In addition, they developed a new formalism of nested coloured timed Petri nets (NCTPNs) by integrating the advantages of nested Petri nets (NPNs), coloured Petri nets (CPNs), and timed Petri nets (TPNs) (Zhang and Rodrigues 2010). These studies did not extend to the computational implementation of production configuration based on the proposed models. Moreover, these studies did not discuss the effect of the several combinations of production objectives on the final configuration results according to company's production characteristics. The study of (De Aguiar et al. 2011) introduces a mixed validation approach for manufacturing cells with multiple robots, which consists of coloured timed Petri nets that models and represents the activities and behaviour of the cell and 3D graphic simulation to simulate, analyze, and validate the behaviour of cell in a 3D environment. The proposed method was decomposed into four steps: (1) Production Flow Schema (PFS) modelling that organize the activities of the cell component, (2) identification of communication protocol data which defines the semantics and syntax of the information which have to be transferred among the components, (3) CPN modelling that formalizes the PFS model and communication among the components and (4) 3D modelling and simulation which convert the CPN model into 3D simulator programming language. Over the past three decades, the manufactures were challenged by market changes of multiple products (models) with small batches. Consequently, models are assembled simultaneously on a same manufacturing line. Nevertheless, an assembly line is challenged by balance problem. Therefore, Su et al. (2014) developed a coloured-timed Petri net model to describe the task precedence relationship on balancing a mixed-model assembly line. Two-stage heuristic algorithms are developed to solve the problem. In the first stage, based on the Petri net model, a P-invariant algorithm (PA) is proposed to minimize the number of workstations. In the second stage, PA is combined with a binary search algorithm (BSA) to minimize the cycle time.

3.1.2 Stochastic Timed Petri Nets

Stochastic Petri nets (SPNs) and generalized stochastic Petri nets (GSPNs) are two popular extensions of Petri nets. Both have been vastly used in modelling, controller and analysis of manufacturing system. There are several studies in the areas of manufacturing system. Zhou et al. (1990) used stochastic PN modeling based on top-down and bottom-up approaches to analyze the performance of FMS under both deadlock free and 'deadlock-prone systems and makes a performance comparison between them. The author fond that a deadlock-free controller is favored if system's supervisory controller is constructed based on a Petri net model. Performance is often essential in the design and development of systems. It is not always enough to know that systems work properly they must also work effectively**.** The study of (Al-Jaar and Desrochers 1990) uses generalized stochastic Petri net (GSPN) modules as basic building blocks to model and analyze complex manufacturing systems. They analyzed the performance of machining workstation controller, transfer lines, and production networks. The performance measures are average production rates and average in-process inventories. The authors found that the GSPN is a valid, flexible, and powerful tool for evaluating several manufacturing systems. New extended stochastic high-level evaluation Petri nets (ESHLEP-N) presented by (Yan et al. 1998) which are more suitable for modelling and simulation of flexible manufacturing systems (FMSs). Based on this model, the scheduling and simulation expert system for the FMS is designed and established. The authors found that Scheduling and simulation expert system is effective. Generic SCPN sub models of machines and conveyor systems was developed by (Moore and Gupta 1995). Three Sub models was combined into a manufacturing system model of arbitrary size. The three sub models include a machine with failures, repairs, and limited size of input and output buffer. The generic sub models were shown to be live and bounded. The qualitative analysis and quantitative analysis can be carried out on the individual sub models. The larger model is composed and color added to distinguish between different types of parts and the resulting model converted to a simulation program and simulated to analysis the performance of the model.

The simulation of the manufacturing system and performance measure using Petri nets provides the possibility to view the manufacturing process in time. Zimmermann et al. (2001) presented generalized stochastic Petri net approach for modeling and analyzing tandem AGV systems. Proposed approach are built by combining the move, transfer, and process, And it is capable of providing analytical as well as simulative results and allows tandem AGV systems to be fully explored within a single modeling framework. Analytical analysis for tandem AGV systems can be performed if the interarrival and service times are assumed to be exponentially distributed. Simulative results require general distributions can be used, and thus do not require this restriction. Performance analysis of production lines is affected by the failures and the repair of the machines. As a results, Liu et al. (2008) discussed the modeling and performance analysis of production lines consist of two machine subject to failures. Two failure detection methods and three interrupted-job-handling policies are considered in their studies. A performance comparison between three examples is done. It is concluded that the repairing sequence rule offers much better performance in decreasing the loss of time and cost due to failure. The work of (Patel and Joshi 2013) develop Stochastic Petri nets (GSPN) model for a manufacturing system with deadlock to generate the reachability tree. Simulation is used to measures the performance and find out the minimum number of parts required to keep some level of throughput of the manufacturing system which consist of Machines, AGV and L/D station. The developed GSPN model is analyzed using Markovian methods. The authors discussed a scheduling problems and the results pertaining to reachability tree analysis. GSPN provides an opportunity to visualize the manufacturing systems modeling in different aspect. Flexible manufacturing systems are complex and need in analysis and evaluating the system before implementing them to obtain the optimum productivity. Coman and Ionescu (2014) used Stochastic Petri nets to evaluate performance measures such as utilization rate of machines, deadlock detection, cycle time, and throughput rate of system.

3.1.3 Fuzzy Timed Petri Nets

Fuzzy theory and petri net are combined to increasing the power of the modeling and analysis of complex manufacturing system. To compute fuzzy firing dates, uncertainty and imprecision within Petri net theory introduced by (Valette et al. 1989) in order to take into consideration abnormal events and the operation for the monitoring and control of manufacturing systems. The method is based on amendment of the marking of a Petri ne model with objects, and through time handling. Fuzzy timing in a high-level Petri net introduced by (Murata 1996). He presented and discussed four fuzzy set theoretic functions of time, these functions, fuzzy timestamp, fuzzy occurrence time, fuzzy enabling and fuzzy delay. The author found that the fuzzy-timing nets are appropriate for time-critical applications since fuzzy time can be calculated very quickly. The study of. Yeung et al. (1999) develops a Fuzzy Coloured Petri Nets (FCPNs) model for analysis of the dynamic behavior of flexible manufacturing systems. The authors integrated the concepts of coloured Petri nets and fuzzy Petri nets. A new weighted fuzzy production rule evaluation method has been suggested to propagate the traditional rule evaluation approach. The approach can be used in controlling of flexible manufacturing processes. A new version of fuzzy timed PNs which incorporates time with the interval and fuzzy set-based models of temporal relationship was introduced by (Pedrycz and Camargo 2003). They show an effect of the time factor on the performance of the model in terms of firing of the transitions and the allocation of the level of marking of the input and output places. Ding et al. (2005) presented a new fuzzy timed Petri net model. In this study, each transition is associated with a fuzzy number. The performance analysis for the model is based on the reachability graph. To compute reachable states for Fuzzy Timed Petri Net model (FTPN), (Ding et al. 2006) developed an algorithm and concluded that it is easier to implement a discrete Fuzzy Timed Petri Net model, but for a theoretical study and understanding of the system behavior the continuous- FTPN model is better. Tüysüz and Kahraman (2010) suggested method for modeling and analysis of dynamic systems using stochastic PNs together with fuzzy. This method consist of two stage which combines two theories, PNs and fuzzy which aims to increase the power for modelling and analysis of discrete event dynamics and complex system. The first stage is same as the conventional stochastic Petri nets. In the second stage, the transition firing rates are represented by triangular fuzzy parameters and then by implementing fuzzy mathematics. The authors found that the suggested method can be used for modeling and analysis of discrete event dynamic and complex system modeled by SPNs.

3.2 PNs with Control

Most important studies in control using Petri nets are focused on deadlock control for manufacturing systems. A deadlock is a situation, which occurs when a process or thread enters a waiting state because a resource requested is being held by another waiting process, which in turn is waiting for another resource. If a process is unable to change its state indefinitely because the resources requested by it are being used by another waiting process, then the system is said to be in a deadlock. To overcome the deadlocks in manufacturing systems, there are three major applied strategies which are deadlock detection and recovery, deadlock avoidance, and deadlock prevention. This section is classified into three groups, detection and recovery, avoidance, and prevention deadlocks.

3.2.1 Deadlock Detection and Recovery

From the aspect of deadlock detection and recovery, resources allocation are processed without any verification. Therefore, the status and requests of these resources are checked periodically to determine if there is a set of deadlocked processes. This checking is achieved by using suitable recovery and detection strategies. There are three types of strategies can be taken for recovery: process termination, resource preemption, and resource reservation. In process termination case, each deadlocked process is eliminated at a time until the all deadlocks disappear. In resource preemption case, a process that is not one involved directly in the deadlock is carefully chose from which enough resources are preempted such that they are made available to deadlocked processes to resolve the deadlock. In resource reservation case, the resources reserved (deadlocked processes) are beforehand called by this strategy, such that the deadlock can be disappeared. The main requirement of these strategies is that the strategies must detect all possible deadlocks in the system. However, the disadvantages of these strategies are that the resource preemption is in general infeasible in FMS and implementation requests human workers and, thus, may be highly expensive.

Few studies have been performed on deadlock detection and recovery based on a Petri net models. The works in (Viswanadham et al. 1990, Odrey and Mejí 2003, Odrey and Mejía 2005) are usually considered to be earlier and seminal researches that consider the deadlock recovery as a special case of error recovery. The primary drawback of the detection and recovery policies is that they often restrict the use of multiple capacity resources and the system performance measures. Therefore, Fanti et al. (1996) developed a graphical and theoretical method for deadlock detection and recovery in an FMS whose resources have multiple capacities. The concept of maximal-weight zero-outdegree strong components is considered to distinguish and detect deadlocks appearance. When a deadlock is detected, an automatic procedure is initialized using a reserved central buffer with a unit capacity to resolve the deadlock. The efficiency of the developed detection/recovery policy is evaluated through computer simulation. Their work represents the first step towards the development of real-time control policies that avoid deadlock in manufacturing systems with multiple capacity resources and performance measures. The work of (Leung and Sheen 1993) proposes two real-time control policies to resolve deadlocks in a flexible manufacturing cell. The first one follows the deadlock avoidance strategy while the other detect a deadlock state. Computer simulation is used to evaluate the performance of policies. The simulation results show that the proposed deadlock policies have a significant effect on the performance of the FMC. In addition, the results indicate that the policy of the deadlock avoidance type outperforms the other one. The drawback of proposed policies is that they always resolve a deadlock in FMC but are not claimed to be optimal.

It is evident that the production-scheduling models are used to determine detailed schedules of parts although the deadlocks that can be caused by part flow are not considered. In order to tackle deadlocks Kumaran et al. developed a structured model based on graph theory for deadlock detection, avoidance and resolution caused by part flow in manufacturing systems. Deadlock detection is designed to detect deadlocks in the system; deadlock avoidance is designed to restricting parts movement so that deadlocks are completely avoided in the future. While deadlock resolution is designed to judiciously using a limited queue to recover from deadlocks (Kumaran et al. 1994). The study of (Wysk et al. 1994) presents two methods based on graph theoretic approach to resolve deadlocks, which are a voidance and recovery. These methods can be used to avoid deadlocks during active control of the FMS. Computer simulation is utilized to evaluate the performance of two methods. The simulation experiments was performed using two factors, which are transportation time and routing intensity. Moreover, based on graph theoretic approach Kim and Kim proposed an easily deadlock detection and avoidance methods (Kim and Kim 1997). The drawback of their methods is that they cannot used if the system configuration is changed. The work in (Basile et al. 2001) contributes a general approach that combines structure (siphon) and marking estimates of a Petri net for supervisory control problem. The inaccurate marking estimate may lead to a worse performance of the closed-loop system and deadlocks. The deadlocks determined by checking whether a particular deadlock condition is satisfied. If the controlled system satisfies the condition and, consequently, no further event is observed for a sufficiently long time, an automatic deadlock recovery procedure is initiated. The marking estimation and deadlock recovery of a place/transition (P/T) based on event observation are discussed in (Giua and Seatzu 2002). In this study, the net structure is assumed known and the initial marking is partially or totally unknown. They proposed algorithms to compute a marking estimation that is a lower bound of the actual marking. The estimated marking generated by the observer is used to design a state feedback controller for forbidden marking specifications. The drawback of this study is that not all enabled transitions to fire are observable, that is to say, the estimated marking is not a lower bound of the actual marking. Therefore, it is necessary to extend the proposed approach. In the study of (Yeh 2002), a dynamic-edge graph (DEG) with double labels is designed to model the AMS, identify distinct part flows, represent the states and capture the concurrent behaviour of the AMS. Moreover, an algorithm based on the DEG and double labels has been proposed to detect the circuit that causes deadlocks and to recover deadlocks in an AMS. Their study indicates that the proposed algorithm can be easily implemented to serve as a functional module for the operation of an AMS. Besides, material such as input/output and error handling procedures can be quickly added to fit each specific case.

3.2.2 Deadlock Avoidance

Deadlock avoidance methods are of vitally importance for automated manufacturing system control in order that correct deadlock-free resource allocation decisions can be made and continuing system operations can be guaranteed. Deadlock-free operations of flexible manufacturing systems (AMS) are essential for increasing the productivity and utilization. Petri net (PN) model of dynamic resource allocation and concurrent job flow in flexible manufacturing system developed by (Banaszak and Krogh 1990) and also defined the deadlock in expression of transition enabling in the Petri Net model. Restriction policy is used to address the deadlock avoidance .The proposed deadlock avoidance algorithm showed and proved that deadlock can never appear for any resource allocation policy applied under this algorithm. The deadlock avoidance algorithms reported by Roszkowska et al. (Roszkowska and Jentink 1993 and Banaszak and Roszkowska 1988) are usually considered to be classical and seminal work in deadlock control using Petri nets. (Abdallah and ElMaraghy 1998) proposed hybrid approach which merges deadlock avoidance and prevention for special class of Petri nets. Dynamic resource allocation policy is implemented to controlled system when the deadlock prevention stage cannot remove deadlocks to minimize the probability of deadlock occurrences. Therefore, this method is not feasible in highly automated manufacturing system.

The design of automated guided vehicle systems (AGVS) has to take into account some management problems such as deadlocks. Using colored resource-oriented Petri net (CROPN), the work of (Wu and Zhou 2004) handles the modeling, deadlock avoidance, and conflict resolution in AGV systems using bidirectional and unidirectional paths. The authors found that the proposed method can construct colored resource-oriented Petri net models for changing AGV routes and there are needed for more studies to decrease the computational potential by restricting AGV layout and routes to certain scopes. The work of (Wu and Zhou 2005) used colored resource-oriented Petri nets to model AGV system and part processing processes. The contributions of their work are two pronged. First contribution, AGV system and the part processing models are integrated by macro transitions. Second contribution, deadlock avoidance method is developed. The result showed that this method does not minimize the complexity for controlling the AGV system. Thus, the developed method may be useful when AGV system is applied by robots. The work of (Wu and Zhou 2007b) aims to identify the shortest routes for a bidirectional AGV whilst both deadlock and blocking are avoided. Compared with other method, the proposed policy can present better solutions. Additionally, the performance analysis of the proposed method is performed via experimental studies. Existing work for automated manufacturing system with robots treating the robot solely as material handling devices and shows that the robots contribute to deadlock. The study of (Wu and Zhou 2007a) used CROPN to model automated manufacturing system with robots as material handling system. Instead, the robots have no contribution to deadlock and can be used to resolve deadlock by dealing them as MH and temporary buffer. In this study, deadlock control method is developed which is more permissive than the existing policies. Yue and Hu (2013) presented a deadlock avoidance policies for flexible assembly processes (FASs), this policy consists of a nominal policy and three concrete algorithms. The time complexity of the presented deadlock avoidance policies is polynomial with the size of the system of tree process net with resources, wherever the system of tree process net with resources Petri-net subclass has the advantage to model FASs in a parameterized and modular way. Therefore, the DAP can be effectively applied for large real-world systems.

3.2.3 Deadlock Prevention

Deadlock prevention widely have achieved for automated manufacturing systems (AMS) and led to a huge number of results. Deadlock prevention is usually achieved by using a computational mechanism to control the request for resources to ensure that deadlocks never occur. In this section, deadlock prevention strategies are reviewed by using Petri nets and developed based on different techniques such as structural analysis and reachability graph analysis.

3.2.3.1 Structural Analysis Approaches

3.2.3.1.1 Siphon-Based Policies

A compositional method for modeling flexible manufacturing systems through a special class of Petri Nets which called S3PR illustrated by (Ezpeleta et al. 1995). Essentiality, this class is constructed from state machines sharing a set of places modeling the availability of system resources. The analysis of special class of Petri Nets leading to describe deadlock situations in case of a zero marking for some structural objects called siphons. They proposed method for resource allocation based on the addition of new places to the Petri Net model imposing restrictions that prevent the existence of unmarked siphons. The authors found that the proposed method is very interesting while dealing with systems for which a deadlock situation is not acceptable. A mixed integer programming based deadlock detection method is utilized to find some minimal siphons in a Petri Net model without accomplish siphon enumeration. For each siphon established, depending on its non-controllability, control places is added such that it is invariant-controlled. Their siphon control technique ensure that no control- caused siphon is ensured due to the addition of the control places. The siphon proceeds iteratively till there is no unmarked siphon in the supervisor of a controlled model (Li et al. 2007). This study is compared with the work of (Ezpeleta et al. 1995), the novel deadlock prevention approach can usually lead to a structurally simple liveness-enforcing supervisor by adding only a small number of control places and arcs. A practical flexible manufacturing system (FMS) example is used to show the suggested approach, it does not improve the behavioral permissiveness. A selective siphon control approach developed by (Piroddi et al. 2008). The major problem for developed method is the computational complexity. At each step, this approach require to calculate all minimal siphons and all dominating markings and solve a set-covering problem. All steps are NP-hard in theory with respect to the Petri Net size. Piroddi et al. (2009) used MIP-based deadlock detection method to improve the developed method by avoiding the complete minimal siphon enumeration. (Chen and Li 2011) solved this problem by mixed integer programming problems. A novel deadlock prevention method for Petri nets that model FMS using siphon presented by (Li et al. 2011). Presented method is added appropriate control place to make each siphon marked until the controlled model is live.

By looking the presence of uncontrollable transitions, Zhu (2012) suggested a deadlock prevention method for special class of Petri nets. Deadlocks are prohibited by siphon control approach, control places are added to model. Linear programming techniques are used to find transitions to which a control place in order that a more permissive liveness-enforcing Petri net supervisor can be established. The study of (Wang et al. 2014) deals with the problems of computational and structural complexity in designing maximally permissive liveness-enforcing supervisors for a class of Petri nets called Systems of Simple Sequential Processes with Resources (S^3PR) without ξ-resources. They used two steps to obtain supervisor for the model, the first step, proposed an algorithm to extract a desired emptied strict minimal siphon (SMS) from a given emptied siphon based on loop resource subsets. The second step, proposed a siphon-based deadlock prevention policy, which can obtain a maximally permissive liveness-enforcing supervisor with reduced structural complexity and no weighted monitors. Several flexible manufacturing systems are used to show the proposed method and its superior performance over the previous ones.

3.2.3.1.2 Elementary Siphon-Based Policies

Strict minimal siphons in Petri net model are classified into elementary and dependent (redundant). The number of elementary siphons in a Petri net is bounded. For each elementary siphon, control place is added to the Petri Net model so that the siphon is invariant-controlled. When all elementary siphons are controlled, the controllability of a dependent siphon is guaranteed. Petri net model for flexible manufacturing system having 26 places, 20 transitions, and 18 strict minimal siphons investigated by (Li and Zhou 2004). A liveness-enforcing Petri net supervisor is computed using the concept of elementary siphons by adding six monitors to control the six elementary siphons among the 18 strict minimal siphons. However, the method described by ((Ezpeleta et al. 1995) needs the design of control places for all 18 strict minimal siphons. Li and Zhou (2006) developed a two-phase deadlock prevention method. The first phase adds a control place for each elementary siphon derived from the MIP-based deadlock detection approach. The output arcs of a control place lead to the source transitions of net model. The second phase rearranges the output arcs of the control places. Deadlock prevention method based on P-invariants and elementary siphons of Petri nets developed by (Li and Wei 2007) for class of Petri nets that can model numerous flexible manufacturing system. Based on P-invariants and elementary siphons of Petri nets, a deadlock prevention method is developed by (Li and Wei 2007) for a special class of Petri nets that can well model many FMS. A diversity of deadlock control method based on Petri nets theory suggested for (AMSs) with unreliable resources by (Liu et al. 2013). Control places are designed for unreliable resources and strict minimal siphons. Control places, complementary places of control places, and recovery subnets are linked by inhibitor arcs in terms of exigency. By adding Control places for siphons, deadlocks in original models can be prevented by adding recovery subnets, complementary places of control places, and needful arcs for unreliable resources. They concluded that this work can be implemented on more complex cases in which the reliability of resources is completely supposed. Hou et al. (2014) developed a novel deadlock prevention policy for a class of generalized Petri nets, namely S^4PR that can well model flexible manufacturing systems (FMS). The concept of elementary siphons guides their efforts towards the development of structurally simple liveness-enforcing supervisors. Therefore, insufficiently marked siphons can be classified into elementary ones and dependent ones. The controllability of a dependent siphon can be ensured by properly supervising its elementary ones. In order to find a compact and proper set of elementary siphons for S^4PR, the concept of augmented siphons is proposed. Then, the concept of max′-controlled siphons is employed, which can relax the siphon controllability condition. By explicitly controlling elementary siphons via adding monitors, a liveness- enforcing controlled system can be found. Transitions are usually assumed to be controllable and observable in most of the existing deadlock control policies for Petri nets. Unfortunately, unobservable and uncontrollable transitions usually exist in practice. In the real world, unobservable transitions denote the events that the controller cannot detect and uncontrollable transitions implies the events that can happen unpredictably. Therefore, Qin et al. (2015) developed an elementary-siphon-based deadlock control policy for flexible manufacturing systems with uncontrollable and unobservable transitions. First, all emptiable minimal siphons are computed, and divided into elementary and dependent siphons. The complementary set of an elementary siphon is expanded by considering unobservable and uncontrollable transitions successively. Monitors are added for these expanded sets. After that, an iterative algorithm is formulated to obtain a live controlled system. It is shown that the proposed policy can design a supervisors for more general Petri nets with uncontrollable and unobservable transitions.

3.2.3.2 Reachability Tree Analysis Approaches

The work introduced by (Viswanadham et al. 1990) is considered to be seminal research and earlier that presents the use of Petri nets in modeling and deadlock control of FMSs. In this study, a deadlock prevention algorithm based on static resource allocation policies is developed for eliminating deadlocks, a reachability graph of the Petri net (PN) model is used to reach static resource allocation policies. The developed algorithm is implemented for a small size manufacturing system, which consisting of a machine and an automated guided vehicle (AGV). The authors observed that the proposed algorithm is claimed to be applied effectively only for small size manufacturing systems.

To avoid a complete state enumeration, Li and Hu (2009) proposed two methods to remove monitors from a Petri net supervisor. The first method is based on the concept of implicit places. It is shown that the implicity of a monitor is determined by solving an LPP that can be performed in polynomial time. The second method is derived from the MIP-based deadlock detection method. If the removal of a monitor does not change the optimal solution of an MIP problem developed from the controlled system, then the monitor is implicit, or its removal may lead to more permissive behavior while liveness is preserved. The work of (Uzam 2002) develops an approach to the design of an optimal Petri net supervisor using the theory of regions that originally aims to provide a formal methodology to synthesize a Petri net from a transition system. An improved version of the work in (Uzam 2002) can be found in the work of (Uzam 2004). He found that the size of the reachability graph is the only problem for applying the deadlock prevention policy to very large Petri net model, in order to avoid this problem Petri net reduction approach is used to simplify very big petri net model so as to make necessary calculations easily in order to obtain an optimal deadlock prevention policy for FMSs. Uzam and Zhou (2007) developed an iterative deadlock prevention approach based on the theory of regions, In their study, the reachability graph of a plant is divided into two parts: the deadlock-free zone and the deadlock zone. The live zone is developed since the maximal strongly connected component contains the initial marking. The deadlock zone contains markings from which the initial marking is unreachable. FBM is defined as a marking in the deadlock zone. The deadlocks can be eliminated by forbidding the firing of the enabled transitions at FBM's. It is shown that the presented approach has two problems. First, an optimal supervisor cannot be guaranteed in general even if such an optimal supervisor exists. Second, at each iteration full reachability graph computation is required to check whether the markings in the deadlock zone are reachable. In theory of regions method all legal and live maximal behaviour of Petri net models can be preserved by using marking/transition-separation instances (MTSIs) or event-state-separation-problem (ESSP) methods. The number of linear programming problems (LPPs) of legal markings is also exponential with net size when a plant net grows exponentially. Therefore, (Huang and Pan 2011) developed a novel methodology to reduce the number of MTSIs, ESSPs and LPPs. They claim that the advantage of the proposed policy is that a maximally permissive controller can be obtained with drastically reduced computation and the experimental results infer that their proposed policy seems to be the most efficient policy among existing methods. Finding an optimal supervisor control design is NP-hard. The studies of (Chen and Li 2011, Chen et al. 2011, Chen et al. 2012a) present and improve a novel and computationally efficient methods to design optimal control places and an iterative approach that only computes the reachability graph once to obtain an optimal supervisor of the FMS, which is expressed by a set of monitors. By using a vector covering approach, the minimal sets of legal markings and the FBMs are computed. At each iteration, an FBM from the minimal set is selected. By solving an integer linear programing problem (ILPP), a place invariant (PI) is designed to prevent the FBM from being reached and no marking in the minimal set of legal markings is forbidden. The objective function of the ILPP maximizes the number of FBMs that are forbidden by the P-invariant. This process is carried out until no FBM can be reached. To make the problem computationally tractable, Binary Decision Diagram (BDD) is used to compute the sets of legal markings and the FBM and to solve the vector-covering problem to obtain the minimal sets of the FBM and legal markings. It is worth noting that this work offers an optimal supervisor for a large Petri net model with 48 places and 38 transitions based on the work of (Li and Zhou 2005) by computing all reachable markings. If the ILPP has no solution, which implies that there is no maximally permissive Petri net supervisor for the model, another ILPP is designed to remove the least number of legal markings whose reachability conditions contradict others markings. Then, a PI is redesigned to keep the remaining legal markings reachable. This process is carried out until no FBM can be achieved. Finally, the most permissive liveness-enforcing supervisor is obtained (Chen et al. 2012b). Based on the methods that developed by (Chen et al. 2011), Chen et al. (2014) developed a place invariant based deadlock prevention method to obtain a maximally permissive Petri net supervisor with the lowest implementation cost. From the viewpoint of implementation cost, a supervisor contains two parts: control places and arcs. For all arcs in a supervisor, they classified them into two parts: control arcs and observation arcs. Then, by assigning a control cost and an observation cost for each transition, and an implementation cost for a control place, the implementation cost of a supervisor can be evaluated. Therefore, two ILPPs are developed to minimize the implementation cost of the supervisor by considering cases. They claim that there is a problem in the proposed method, i.e., computational complexity. First, it is based on reachability graph analysis of a Petri net model, which suffers from the state explosion problem. Second, the proposed two ILPPs have too many constraints and variables for large-scale Petri net models, which makes them inapplicable to real-word systems.

3.2.3.3 Structural- Reachability Analysis Approaches

The work of (Wei and Li 2008) can be considered as an improvement of the theory of regions. First, theory of regions approach is used to design a supervisor for a plant net model to find the maximally permissive behavior. Then, the strict minimal siphons in the maximally permissive controlled system are computed and divided into elementary and dependent siphons, algebraic expressions is used to prevent siphons from being emptied. Moreover, the expressions are used to derive the live initial markings for the supervisor without changing the supervisor's structure when the initial marking of the plant changes. Li et al. (2004) and Li et al. (2008) developed a two-phase deadlock-prevention policy by siphon control and the theory of regions to reduce the number of MTSI. First, strict minimal siphons are identified through resource circuits only and controlled by monitors. Then, the theory of regions is applied to the augmented Petri net with monitors to find a supervisor. The three studies show that the combined method is computationally efficient compared with existing methods in which the theory of regions is used alone, and the permissive behavior of the supervisor is near optimal.

4 Conclusions and Open Problems

In this study, Petri net applications in the area of modeling, analysis, and control of manufacturing systems were reviewed; also the historical progression in this field was emphasized. The main force behind this work has been the growing interest in applying PN theory for modeling, analysis, and control of manufacturing systems. Figure 2 illustrates the distribution of 94 published papers during the period from 1988 to 2015. From the Figure 2, we found that most usage of Petri net is in control application specifically in deadlock prevention due to the large and continuing stream of efforts.

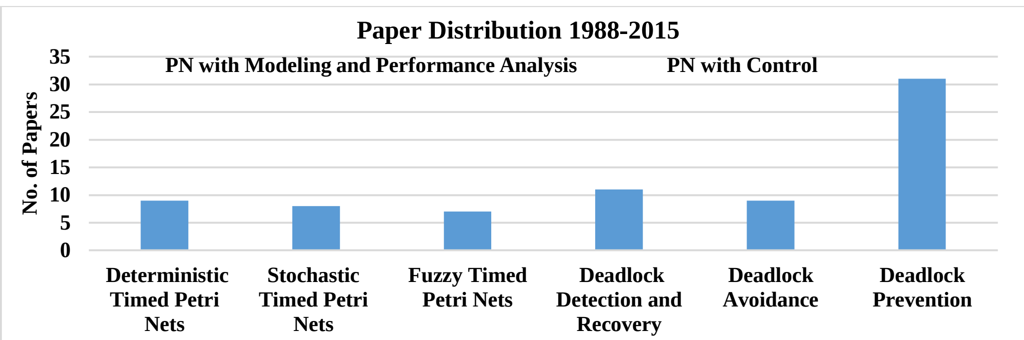

Figure 2: Paper distribution for period 1988-2015

The research points from the literature review can be summarized as follows:

4.1 Problems in Modeling and performance analysis

- Most of works used deterministic and stochastic petri net for modeling and analysis of manufacturing system with reliable resources while manufacturing systems consisting resources with unreliable resources. Therefore, there is a need to develop models based on Petri nets with stochastic failure process and a repair process.
- The problem of constructed colored resource-oriented Petri net (CROPN), it requires, in the worst case, the exponential time to identify all the circuits, cycle chains, and their relationship, more studies are needed to reduce the computational effort by restricting AGV layout and routes to certain scopes.
- Scheduling plays a very important role in many modern manufacturing and production systems, which involves multi-objectives and multi-machine environments. A scheduling system based on PNs and a rule base has been extensively used to make decisions for on-line scheduling, and to evaluate the different scheduling policies. Since PN based simulation with heuristic dispatching rules and metaheuristics provides an acceptable solution for the dynamic scheduling problem in a shorter time, it continues to gain increasing attention for practical scheduling problems.
- Modeling and analysis of manufacturing systems based on PN are a productive area for researchers. The future research issues have to handle the large-scale, configurable and complex manufacturing systems. Several combinations of production objectives should be considered to study their effects on the system performance.

4.2 Problems in Control

- Most of the researchers have used structural analysis and reachability graph analysis to design deadlocks prevention policies for different scales of AMSs under three criteria that are maximal permissiveness, structural complexity, and computational complexity. The comparison between of these policies has been done according to the three aforementioned criteria. It is taken for granted in the literature that a maximally permissive supervisor in the logical level usually leads to the better time performance in an AMS such as productivity and resource utilization, which looks intuitive, as an optimal supervisor will permit more permissive behavior. However, there is a shortage in the quantitative evaluation of time performance of these policies in term of maximal permissiveness and productivity. Simulation is a powerful tool for performance analysis of complex manufacturing systems.

- Unreliable resources or fault occurrences are common in real-world systems. Failures can cause a part of a system or the entire system to shut down, which deteriorates and degrades the performance of manufacturing processes. Broadly speaking, deadlock control under unreliable resources belongs to the supervisory control of systems with unpredicted occurrences of new control specifications. A robust liveness-enforcing supervisor is a supervisory controller that can control a system with unreliable resources. Therefore, there is a need to develop a supervisor under dynamic control specifications.
- The developed deadlock control methods are used to prevent the deadlocks in the manufacturing systems. However, the controlled manufacturing systems have not been converted into PLC implementation to evaluate if the deadlock control methods applicable for the execution of automation tasks and show drawbacks, and strengths of these deadlock control methods.
- Most of developed deadlock control methods designed for pure Petri net (not including self-loops, enabling arcs or inhibitor arcs) and may not lead to optimally controlled systems. Nevertheless, there may exist deadlock control methods with non-pure Petri net, which may lead to optimally controlled systems. However, mathematically representing a non-pure net structure is not an easy and needs large efforts.
- From the survey, we found that the developed deadlock control methods based on Petri nets models have implemented on generated manufacturing systems, that is to say, they are theoretical studies. Therefore, there is a lack of application in real-world systems and deciding if they are applicable for industrial and computer companies.

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