Role of Petri Nets in Flexible Manufacturing System – A Review

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Abstract — *Petri Net is a technique based on the graph theory leading to a network that can model parallel, concurrent and simultaneous activities in scheduling and then to solve the problems of deadlocks, overflows, tool management, etc. in a Flexible Manufacturing System (FMS). Such issues are being solved both in terms of qualitative and quantitative aspects of an FMS and evaluated easily by the Petri Net models. The paper presents a brief survey of sixty seven published research papers related to Petri Nets (PN) in modelling of FMS and its modules to solve the different kinds of issues.*

Keywords — *Petri Nets, Colored Petri nets, FMS, Modelling, Scheduling, Deadlocks, Overflows, Tool Management.*

I. INTRODUCTION

Flexible Manufacturing methods have been adopted broadly in modern computerized manufacturing environment. It has various advantages over traditional manufacturing systems, such as shorter set-up time, lower inventory, higher quality, etc., since the introduction of the cellular manufacturing concept. As such, FMSs have been installed in many automated manufacturing systems. A high-level control system has to decide on the assignment of resources to the product and on the particular instant of time, so as to optimize any of the decision criteria. The purpose of scheduling is to determine the processing sequence of the job and the production requirements so as to meet production objectives [1]. Petri Nets are an ideal tool for modelling of FMSs because of their ability to capture the characteristics like parallel, concurrency, stochastic nature of activities and also can accommodate the constraints systematically so as to achieve single coherent formulation. Using such PNs, various issues in FMS like schedule optimization, deadlocks, tool management, etc., can be tackled easily than other techniques.

II. FLEXIBLE MANUFACTURING SYSTEM

Flexible Manufacturing System is a system consisting of a group of processing work stations inter connected by means of an automated material handling and storage system and controlled and monitored by integrated hierarchical computer control system [52]. A typical FMS can fully process the members of one or more part families on a continuing basis without human intervention and is flexible enough to suit the changing market conditions and product types without much change in existing setup. The sections and the related components of an FMS are shown in Fig. 1 and their related interaction with information flow is shown in Fig. 2.

There are a number of capabilities that a manufacturing system has to possess in order to become flexible. Of them the most important are, [53]:

1. The ability to identify and distinguish among different incoming part or product styles processed by the system.
2. Quick changeover of operating instructions.
3. Quick changeover of physical setup.

A. Background and Objective of the Paper

It is common in the Research and Development area to bring-out the Literature Survey from time to time. As such, [52] has brought a survey paper on Petri Nets, Properties, Analysis and Applications. The recent being the survey and comparison of Petri Net based Deadlock Prevention Policies for FMS [7]. Though, that survey has taken eighty two papers into consideration but individual contribution is not discussed, at least in brief. Therefore, to relax such things the present survey / review on the Petri net in FMS is presented.

III. FMS ACTIVITIES AND THEIR COMPLEXTIES

The FMSs have become very popular due to their productivity, flexibility and adaptability. Such systems are highly complex and their successful implementation is very difficult. Careful planning is essential to realize their full potential. The hierarchical framework of FMS planning has the following levels [38]:

1. Strategic level: Deals with long term decision making related to the technical and economic design of the system

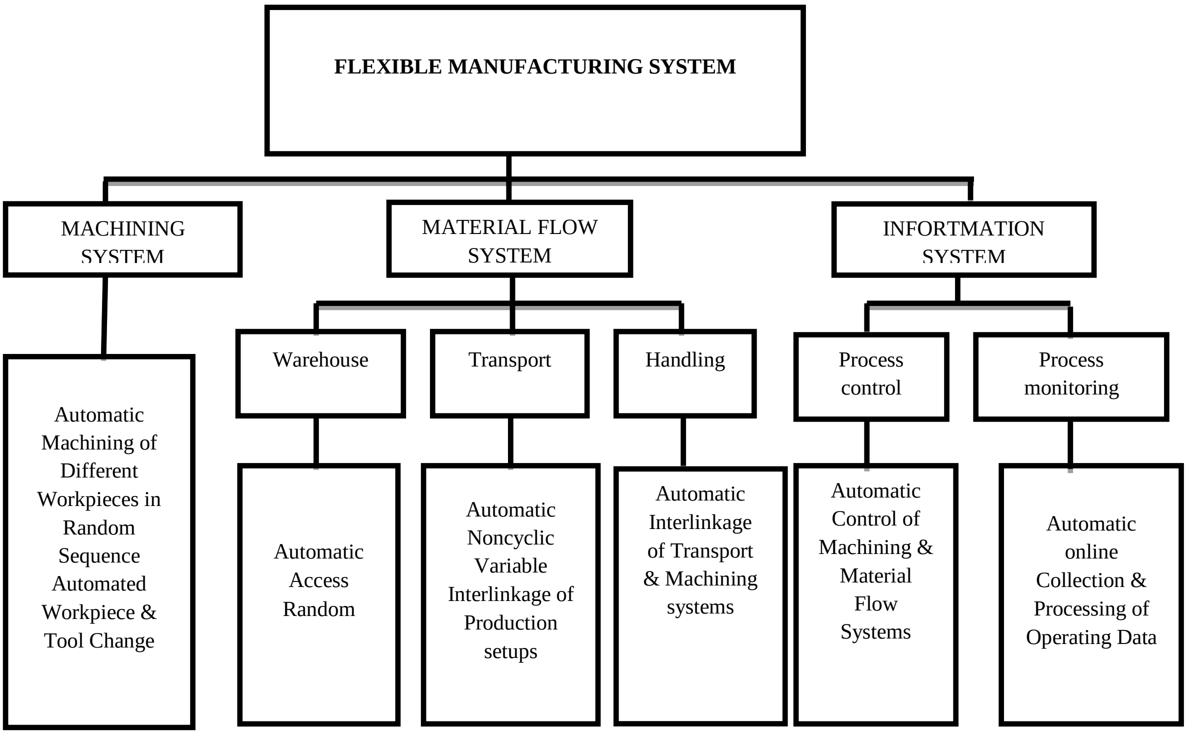

Fig. 1: Components and structure of Flexible Manufacturing System

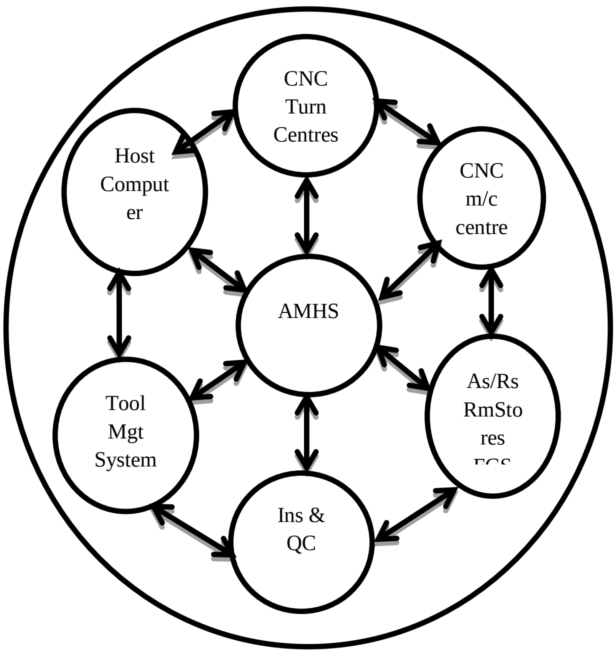

Fig. 2: Components of FMS with interaction and information flow between the sections

2. Tactical level: Concerned with planning issues so as to organize by the efficient and effective usage of the resources.

3. Operational level: Deals with the detailed decision making required for real time operation of the FMS. Decisions made on-line and efficient scheduling are essential for successful implementation.

The FMS scheduling problem is more complex and critical than that of job shop scheduling because the components of a FMS are highly interrelated. Therefore, maximizing the system's utilization in such a complex environment necessitates the use of an efficient scheduling system operating on real time based on the Tool Management, [50]. The scheduling of an FMS is dependent on the deadlock problems which can cause unnecessary costs because of long downtime and low use of some critical and expensive resources in FMS environment. Therefore, the deadlock prevention is essential and depends on a suitable design for deadlock free systems. The goal of the deadlock prevention approach is to aim the system a control policy which prevents the deadlock states.

The computations are carried-out off-line in a static way and once the control policy is established, the system can no longer reach or undesirable deadlock states [58]. Therefore, the development of efficient deadlock prevention policies which can optimize the use of system resources has long been an important issue. Such dead locks have been tackled by three main approaches in FMS environment [18] as shown in the following,

1. ***Deadlock detection and recovery:*** The technique helps to identify the occurrence of deadlocks and communicate the system controller so as to put back the system is to a deadlock-free state, by simply reallocating the resources.
2. ***Deadlock avoidance:*** The approach helps to keep the system away from deadlock states. Although the suggested approach usually leads to better use of resources and throughput, but does not totally eliminate all deadlocks. The next important aspect is related to the Tool Management. Such issues are studied one after the other in the following.
3. ***Deadlock prevention:*** The goal of the deadlock prevention approach is to add to the system a control policy preventing the system from reaching deadlock states.

Tool Management deals with the availability of a right cutting tool, for a right process, at the right time, at the right place and on the right machine [50]. There are five types of tool allocation strategies that are identified in the literature, namely: mass or bulk exchange, tool sharing, tool migration, assigned tools and dynamic tooling [29].

1. ***Mass or Bulk exchange:*** It provides a complete devoted set of tools for each different part type upon completion of specific production requirements. All tools are returned to the tool room and are replaced by a new set of tools for the next part type with-in a fixed production period [32]. Though the strategy results in easy tool exchange; but the control is achieved at the expense of excessive tooling inventory.
2. ***Tool sharing:*** Tool-sharing concept permits the logical sharing of tools within the framework of fixed production period and work piece requirements. Common tooling among the fixed production requirements is recognized and shared among the various parts to be manufactured in the fixed production period. Tool sharing represents a vast improvement over the mass-exchange strategy because identified tools to be shared are not duplicated in each machine's tool matrix for each work piece type, thereby reducing the tool inventory [50]. Also, the shared tool strategy requires computer software to implement because of merging the tool lists and matching requirements to identify the common tooling
3. ***Tool migration:*** The method is an extension of the mass-exchange and tool sharing Modules with functions ranging from issuing tools according to tooling strategy to diagnosing system operation have been developed and integrated around a centralized manufacturing database to guarantee streamlined manufacture. A review of the state of the art tools to model an automated tool management system (TMS) within flexible machining facilities is presented first, in order to establish the merits of different design approaches. The approaches used in modelling, the structures and the functions of the modules are presented [44]. The new design method with artificial intelligence has considerable advantages in modeling. Though this strategy allows a further reduction in tool inventory, it requires the application of sophisticated computer software and decision logic theory.
4. ***Assigned tools or Resident tooling:*** The method identifies the most used tools for the production requirements and part mix, and assigns permanent residence to those tools in each machine tool matrix for the full production run. The proposed deadlock control algorithm deals with the numerical experiments to show that the proposed control algorithm to be more permissive as far as the tools and the scheduling so as to overcome the some kind of deadlocks due to tools [11]. Though, the flexibility to respond to unplanned events and delays is considerably enhanced but the method does not help to minimize tool inventory.
5. **Dynamic tooling:** The technique helps to transport the required tool to the machine when it is needed just-in-time, and a part can be processed on any machine. Then, that has been later supported by the developing a real-time interactive control system in dynamic status for advanced manufacturing systems by combining real-time simulation and expert systems [67]. Though the simulation helps dynamic conditions but the failure condition of the tool is missing. A brief survey on the usage of conventional techniques is shown in the following.

IV. CONVENTIONAL TECHNIQUES

1. Mathematical programming: It has often been used to address FMS scheduling problems. For example, [54] have presented an algorithm to schedule parts to minimize the setup cost. The dispatching problem has been formulated as an extremely large mixed-integer linear programming [56]. Later on, the releasing problem and dispatch rules of a flexible flow shop are modelled for effective scheduling [55]. However, mathematical programming approaches can hardly be used for real-time decision making in view of restrictive assumptions and computational requirements.

2. Queuing models: These models form another potential tool and generally assume the first-come Queuing networks can model the system at aggregate level, but not effective for on-line scheduling and control.

3. Simulation: It has been widely used to address FMS problems at different levels and has been successfully applied to analyze the effect of different releasing and dispatching policies [60]. Further, the simulation model describes the detailed dynamic behavior of the physical systems by consideration of several releasing policies [61] and the part-to-machine dispatching rules are then tested by [63]. A manufacturing cell has been modelled by a hierarchical decomposition algorithm to analyze the scheduling and control issues and proved that a suitable language like ADA makes possible the simulation very efficient [64]. Such modelling techniques ultimately lead to the development of a control software followed by the dynamic scheduling and routing for FMSs that have unreliable machines [65]. Though the simulation is an effective but the overflows make the model slow and deadlocks.

4. Artificial Intelligence: The emergence of artificial intelligence techniques have influenced the FMS scheduling. A knowledge based real-time control mechanisms under varying and unexpected conditions have been proposed [66].

In addition, the analysis relating to the critical time, dynamic and complex systems is modelled with numerical example of fuzzy sets in an FMC which consists of two stages. The first stage is same as the conventional stochastic Petri nets which obtain the steady-state probabilities parametric transition firing rates. The second stage deals with the transition firing rates which are described by triangular fuzzy numbers by the stochastic fuzzy state probabilities [30].

Though, many techniques are being developed to solve the real time production scheduling and control in an FMS, still the issues like overflows, deadlocks, parallel and concurrent processing, etc., require more attention. Therefore, the Petri net models are emerged to tackle such issues during 1962 but published in 1965. Since, then, Petri nets based on the Graph Theory have been used widely to describe manufacturing systems. The behavioral properties of the Petri net model, such as liveness and boundedness, and its structure are captured. The deadlock prevention control policy is then obtained based on the characterization of the liveness in terms of Petri net items (siphons) [59], but their application to FMSs are emerged only during later part of 1980s. The powerful feature of Petri nets is the ability to detect good behavior properties of the system such as deadlock freeness and boundedness. Therefore, first-serve (FCFS) queue discipline [57]. Among the notable Queuing models is the development and implementation of state dependent rules for dispatching and routing of jobs. Though, the the paper presents the role of Petri Nets in general and FMS in particular.

V. PETRI NETS

Petri nets are graphical and mathematical modelling tool applicable to many systems. They are promising tools for describing and studying information processing systems that are characterized by concurrent, asynchronous, distributed, parallel, nondeterministic, and / or stochastic. As a graphical tool, Petri nets can be used as a visual-communication aid similar to flow charts, block diagrams and networks. In addition, tokens are used in the nets to simulate the dynamic and concurrent activities of systems. As a mathematical tool, it is possible to set-up state equations, algebraic equations and other mathematical models governing the behavior of systems. The various characteristics consists of performance evaluation, communication protocols, modelling and analysis of distributed-software systems, distributed-database systems, concurrent and parallel programs, flexible manufacturing / industrial control systems, discrete-event systems, multiprocessor memory systems, dataflow computing systems, fault-tolerant systems, programmable logic and Very Large System Integration (VLSI) arrays, asynchronous circuits and structures, local-area networks, legal systems, human factors, neural networks, digital filters, decision models, etc. [28]. A simple example of Petri net (PN) is shown in Figure – 3 followed by the Petri Net Modelling showing processing of a job on a machine in Figure – 4, [50].

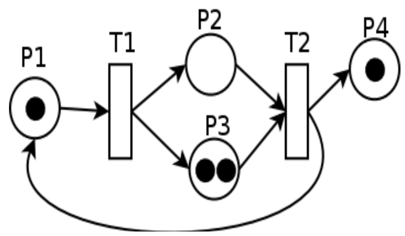

Fig. 3 Simple example of Petri Net Model [28]
(Note: P represents place and T Transition)

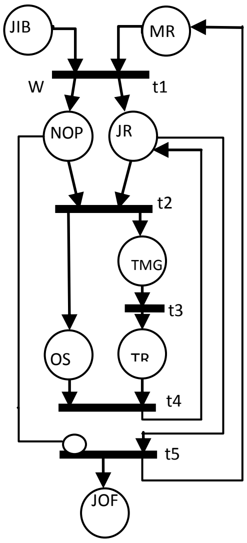

Fig. 4 Petri Net Model (PNM) showing processing of a job on machine [50]

TABLE I
INTERPRETATIONS OF PLACES AND TRANSITIONS SHOWN IN FIG. 4

Places	**Interpretation**
JIB	Job in the input buffer of a machine
MR	Machine ready
NOP	No. of operations to be performed on the part by a machine
JR	Job ready for the next operation
TMG	Tool on magazine available
OS	Operation selected
TR	Tool for the selected operation ready at the machine
JOF	Job in the output buffer of the machine
Transition	**Interpretation**
t1	Loading of the job onto the spindle
t2	Selection of operation to be performed next
t3	Machine performing an operation
t4	Unloading the job from the spindle
t5	Checking for the tool availability
Note : Weight W indicates number of operations	

A. Structural Properties

A major strength of Petri nets is their support for analysis of many properties and problems associated with concurrent systems. Out of them, the important are structural properties and behavioral properties. Structural properties are those that depend on the topological structures of Petri nets. They are independent of the initial marking in the sense that these properties hold for any initial marking or are concerned with the existence of certain firing sequences from some initial marking. The Petri Net variables are shown in Table I.

B. Behavioral Properties

The behavioral properties depend on the initial marking, and those which are independent of the initial marking.

1. ***Reachability:*** Reachability is a fundamental basis for studying the dynamic properties of any system. The firing of an enabled transition will change the token distribution (marking) in a net according to the transition. A marking M, is said to be reachable from a marking M0 if there exists a sequence of firings that transforms M0 to M.
2. ***Boundedness:*** A Petri net (N, M0) is said to be k-bounded or simply bounded if the number of tokens in each place does not exceed a finite number k for any marking reachable.
3. ***Liveness:*** The concept of liveness is closely related to the complete absence of deadlocks in operating systems. A Petri net is said to be, L1-live if, t can be fired at least once in some firing sequence, L2-live if, given any positive integer k, *t* can be fired at least k times in some firing sequence, L3- live if, *t* appears infinitely, often in some firing.
4. ***Persistence:*** A Petri net *(N, M0)* is said to be persistent if, for any two enabled transitions, the firing of one transition will not disable the other. A transition in a persistent net, once it is enabled, will stay enabled until it fires. The

notion of persistence is useful in the context of parallel program schemata.

VI. ROLE OF PETRI NETS IN FLEXIBLE MANUFACTURING SYSTEMS

Usage of Petri nets in the modelling has been emerged during 1960, from the contributions of Petri which won him the Degree of Ph.D. during 1962. The momentum of usage of Petri nets and analysis based on transitions from firing of the nets has gained in the earlier 1980s. Petri net models, therefore, the resulting controlled model of the system is not maximally permissive. That is, the solutions obtained in such case are suboptimal [62]. To overcome such situation in FMSs, a flexible manufacturing system (FMS) model is developed using Petri nets for analyzing the important qualitative aspects of FMS behavior such as existence / absence of deadlocks and butter overflows [39]. It has also been observed that the classical invariant analysis of Petri net related to qualitative properties of the FMS such as existence of deadlocks, buffer overflow, invariance of number of jobs and recoverability from failures is determined. Later-on the FMS has undergone more than four generations by the year 1986 with the emergence Tool Management issues.

To start with, issues are dealt with the analysis of Scheduling, Tool Management, Deadlocks and Overflows, Liveness and Siphons, and Monitoring and Control.

A. Scheduling

Scheduling is a complex issue in FMSs due to the synchronization of machining, communication and control activities. Such activities have led to the development of priority nets for flexible and realistic modelling, and simulation with Petri Nets (PNs). As such, the Petri Nets modelled by extending Timed Petri Nets to impart dynamic decision making capability and flexibility Priority nets. A simulation methodology is proposed for the priority nets by describing a dynamic scheduling algorithm and to determine the operating policies under varying conditions of FMS operation [38]. Once a Timed Petri Net model of the system is constructed, the scheduling algorithm tries to search a partial reachability graph. Depending on the heuristic functions used, the scheduling algorithm finds a globally optimal or near optimal feasible schedule in terms of the firing sequence of the transitions. The formulation explicitly and easily handles the important characteristics such as routing flexibility, shared resources, lot sizes and concurrency. By setting the initial and the final markings appropriately, partial scheduling can be handled without any modification of the model [43]. Such modelling with Petri nets is extended for an integrated hierarchical control and scheduling simulation model for flexible manufacturing cells (FMCs) with colored timed Petri nets (CTPNs) by considering the lower control level and the upper control level of the scheduling.

In the control level, the CTPN model serves as a mechanism to dispatch shop-floor activities within FMCs. In the scheduling level, the same model represents the scheduling process considering the precedence relations, resource and time constraints graphically [40]. The Petri Net with Intelligent Generator of Successor which allows reducing the search effort without losing optimality whereas the Dynamic Window Search heuristic algorithm helps for the effective scheduling and production controls in an FMS [20].

A hybrid AI based scheduling heuristic algorithm Dynamic Look ahead State Search (DLSS) is presented for preliminary and as a promising alternative to overcome the difficulties encountered with previous approaches. The Controlled Generator of Successors called CGS model helps to identify successful alternatives and discard futile ones and finally the Search Frame (SF) behavior rules the strategy by avoiding exponential generation of markings with the search for a solution [13]. An interactive hierarchical two level model based on Colored Petri Net (CPN) for general FMS scheduler is presented, where-in the first level (cell-level) supervises the jobs scheduling between cells and the second level (machine-level) supervises the scheduling of the manufacturing jobs between machines inside the active cells. The highlight of the scheduler is that it facilitates graphical representation so as to achieve the sequencing, dispatching and monitoring the real time execution of the manufacturing plans [48]. Then, the Depth First (DF) strategy is evaluated and demonstrated by the scheduling results derived and evaluated through a simple FMS with multiple lot sizes for each job. The algorithm is also applied to a set of randomly generated more complex FMSs limited buffer sizes, multiple resources, and alternative routings [23]. All such scheduling methods helped for merging of PNs with dispatching rules for measuring the performance of FMSs modelled in MAT lab so as to integrate Petri Net 2.3 software and the traditional dispatching rules. The simulation results show that the dispatching rules provide enhanced result when compared to other two techniques [49]. A Hierarchical Colored Petri Nets Simulation real time Model of an FMS is developed for scheduling by considering the variable process times of workstations. The model helps to find the mean value of the processing time which show that there is a slight difference between the make span of the real production line and the simulated one [14].

B. Tool Management

Tool Management has become an important part of FMS, since more than fifteen thousands of tools are handled in the FMS environment in an eight hour shift. At machine group level, it is proved that the effective tool management could lead to a cut in production time by 30% and 70% reduction in tool preparation time. The authors have described a centralized tool management structure and studied the effects of presence of tool sharing, and absence of tool sharing on the production rate as well as machine utilization. The analysis has proved that tool sharing is advantageous. Furthermore, it is also found that with increasing the number of shared tools, the difference in production rate also becomes wider [50]. Then the problem of tool sharing at a machine group level in FMS is modelled with stochastic Petri nets by considering the uncertainty in activity times of realistic machine tools and batches in competition for handling of tools by AGV. It is concluded that the performance of the system depends on selection of batches and tool sharing. Such batch selection permits not only the obtaining of higher shared tool ratios but also to take into account the tool-disk capacity or the tool life constraints [41].

A heuristic solution model to the machine loading problem of an FMS is developed for the allocation of a job from the job pool maintaining the flexibility of the system, reducing the system imbalance and thereby maximizing the throughput. Though, the proposed heuristic employs the backward procedure to maximize the assigned workload and simultaneously but the complete flexibility of the system could not be achieved due drawbacks of tool changing time and using a predetermined sequencing rule, and tool overlapping [42]. Therefore, an Object-Oriented coloured Petri net with OMT for dynamic tool-sharing control problem is developed with reusability and maintainability. The major advantages of the model are in dealing with the multi-stage multi-machines environment by the consideration of tool delivery system, central tool dispatcher, a tool exchange and storage system under a non-hierarchical shop floor control scheme, in the FMS [29]. To overcome such constraints, a real time tool-sharing philosophy by keeping track of the tool life of each tool processing a job on a machine in terms of total machining time and remaining tool life is modelled with new Colored Petri Nets (CPN) for an FMS having N part types and M stations. The performance evaluation is based on the analytical method and proved that the performance of the system is improved and also the model can be used for simulation and designing large systems. However, there will be a need to adopt pseudo-heuristic such as GA, PSO, etc., [36].

C. Deadlocks and Overflows

Deadlocks and Overflows are the other important issues that make the FMS a complex system thereby delaying the production schedules and leading to financial losses. To overcome such issues the FMSs are modelled with Petri nets and analyzed.

An FMC with desirable properties and synthesis top down refinement, system decomposition and modular composition ideas with hierarchy is modelled with Petri net. The preservation of important system properties including the liveness, boundedness / safeness and reversibility that guarantee the system to operate in a stable, deadlock-free, and cyclic manner are embedded in the model [47]. A given FMS and a set of new net elements, places with initial marking and related arcs, reachability graph using the theory of regions is modelled with Petri nets. The proposed optimal deadlock-prevention policy is not acceptable at all for the considered systems, when some critical and expensive resources are used, and when the on-line system response time is critical [4].

Such overflows and deadlocks are also tried by AI based scheduling heuristic algorithm developed using the Petri net consisting of Part-1 is based on the new B-nets with search heuristic concept for the resource cost reachability matrix based on information obtained from the PN mode [12]. It is extended for the study of Buffer nets to model Part-2, so as to study the (i) dispatching rules using analysis information provided by the PN simulation and (ii) modified stage-search algorithm to reduce the complexity of large systems [21]. Further, an optimal, efficient and Deadlock prevention algorithm is proposed to very large Petri nets considering the ‘‘state explosion problem’’ by simplification of subnet or structure by preserving boundedness, liveness and reversibility [8]. It is followed by the model of an iterative synthesis and a live controlled PNM for deadlock prevention policy in an FMS so as to achieve deadlock-free operation and high performance in terms of resource utilization and system throughput. The proposed method is generally easy to use, effective and straight forward although its off-line computation is of exponential complexity [6]. Considering such issues, a comparative study of Petri Net-Based Deadlock Prevention Policies for FMSs with existing deadlock prevention policies carried-out from the stand-points of behavior permissiveness, computational complexity and structural complexity are brought-out. It is observed that behavior permissiveness is not a major concern and established that the P-policy (set of operations) to be a major choice for industrial size automated systems with polynomial complexity whereas spanning tree – U policies can be considered in case of the offline computational cost is not a problem [7].

Though the survey taken eighty two papers into consideration but individual contribution is not discussed atleast in brief. Therefore, to relax such things the present survey paper on the Petri net in FMS is presented. Resource-Oriented Petri Net (ROPN) for Deadlock Avoidance in the assembly or disassembly processes by capturing the discrete event dynamics of a joint Flexible Assembly System (FAS) is modelled and proposed a deadlock control policy. Another interesting research topic brought-out is the application of digraphs to such complex FAS and the need of ROPNs control policies [27]. A set of inequality constraints is derived from the markings of monitors and the places in the Deadlock Prevention Based on Structure Reuse of Petri Net Supervisors model for FMSs is developed which is capable enough to identify the redundancy condition for near-optimal performance of the plant net and a deadlock-free controlled system without changing the structure [18].

D. Liveness and Siphons

Liveness in a Petri net model of an FMS is dependent on the firing of transitions. Therefore, the structural theory of Petri nets depends on the liveness based on the transitions and their firing sequence for deadlock prevention. In such situations, the necessary and sufficient liveness condition called Systems of Sequential Systems with Shared Resources (S^4R) has been derived for the first time. Such characterization is based on the controlled siphon property. It has been shown that if the augmented net does not present new uncontrolled siphons, then it is live. A deadlock prevention method has been proposed with new uncontrolled siphons by creation of augmented net but deadlock-freeness is not guaranteed. Therefore, an on-line controller has been developed for deadlock avoidance [45].

A new class deadlock prevention iterative algorithm, Extension of System of Simple Sequential Processes with Resources (ES^3PR) from S^3PR with Petri nets is developed so as to relate the unmarked siphons. The method is developed by adding ordinary control place and weighted control place to the original model to prevent siphons and obtain the liveness and reversibility [15]. The ES^3PR is further enriched by modelling with timed Petri nets, of S^4R. The algorithm generates a partial reachability graph to find the optimal or near-optimal deadlock-free schedule in terms of the firing sequence. The model has been proved by experimentation that the siphon truncation technique enhances the ability to prevent deadlock, which cannot be achieved using standard Petri net scheduling approaches [16]. Next, a practical case study presented to show that the number of elementary siphons for control is much less than that of Strict Minimal Siphons (SMS) and further reduction of SMSs for Petri net models of large-scale systems to prevent the deadlocks and overflows [2]. Therefore, synthesizing liveness-enforcing supervisors in an FMS that has been modelled by a class of Petri nets shows that it avoids complete siphon enumeration is more time-consuming for a sizable plant model than the mixed integer programming (MIP) method. First, siphons that need to be controlled are found using the MIP and found by experimentation that it is more efficient than the existing ones. In case of second, the output arcs of the monitors arranged on condition that liveness is further preserved, [3] followed by a MIP based deadlock detection design model to find minimal siphons [5]. A polynomial-complexity deadlock control algorithm to find the set of elementary siphons is developed with Petri Nets in an S^3PR leading to some more general net subclasses [19].

A model developed by using a vector covering set of legal markings with minimal covered set of first-met bad markings (FBM) are also solved by an integer linear programming problem but without siphons. Further, binary decision diagrams (BDD) is used to track the sets of legal markings and FBM [9]. A deadlock prevention design and optimization Petri net based siphon model is presented in an FMS, using S^3PR. The model run on MTAB helps to allocate the tokens in the control places reasonably and guarantee with absence of deadlock states, and that the S^3PR net are invariant-controlled [31]. It is followed by the Petri net models for effective implementation and the prevention of deadlocks [34] and also to enumerate and reduce the reachability graph by adding monitors to all basic siphons [28]. In addition, the effective deadlock prevention policy of a special class with S^3PR is proposed for establishment and optimization of the automated guided vehicle (AGV) fleet size in FMS [25]. An elementary siphon - based deadlock prevention model for a class of generalized Petri nets, called S^4PR having the concurrently cyclic sequential processes sharing common resources is developed. The deadlocks control method that combines the policies relating to Deadlock Avoidance Policy (DAP) of Resource Upstream Neibourhood (RUN) with elementary siphons are max-controlled liveness after adding a monitor for each elementary siphon Consequently, the resulting liveness caused by the insufficiently has marked siphons leading to a more permissive behavior [26].

E. Monitoring and Controls

The performance of any FMS depends on the proper monitoring of the working of the equipment with efficiency and process control. To start with the development of a software design methodology allowing automatic generation of controller logic from a high level system design specification in combination with SADT and Petri Net tools. The model which runs on IDEF has also considered the manufacturing system behavior in a real environment according to its functional specification [37]. For effective modelling analysis, a colored timed Petri net model is developed in order to increase the equipment efficiency, with the inclusion of a statistical process control which helps for failure analysis and fault diagnosis. The model is interfaced with objective-oriented expert system, G2 [10]. Hence, a Generic Petri Net (GPN) control software is developed for online checking the control parts with the help of temporal relationships between physical operations and the specification of the FMS controllers. The GPN makes the controls not only simple but also helps the procedural language for information processing [35]. A robust FMS design with coloured Petri net is modelled as multi objective optimization problem that simultaneously minimizes the production costs under multiple production plans. It is also coupled with a genetic algorithm considering the Shortest Imminent Operation (SIO) dispatching rule. Although the scheduler results in configuration of hybrid scheme allows very fast evaluation of large number of feasible configurations, essential for the robust FMS design but does not guarantee the optimal [17]. The fast communication between the different works stations are brought by modelling a Holonic Manufacturing Systems (HMS) based on Multi-agent systems (MAS) with Petri net theory in contract net protocol to form commitment graphs and award contracts feasibility to meet liveness conditions. Such HMS can also be extended to general MAS [24].

The system performance of an FMS consisting of four machines with virtual batch manufacturing and virtual line manufacturing having flexible process plans for each part type is modelled with Petri nets and analyzed. The analysis based on the performance measures such as make span, mean flow time, maximum flow time and variance of flow time will help the planner in selecting optimum set of operating parameters such as dispatching rule, number of pallets released to the system, etc., [46].

Recently, a parsimonious supervisor design problem is reformulated as a direct monitor optimization task based on integer linear programming, which can more effectively deal with the existence of feasible solutions to the hardness of guaranteeing maximal permissivity and optimality in the size and cost of the control subnet. The efficient branch-and-bound scheme for the exploration of the solution space optimization problem is also embedded and the model has been tested on a well known benchmark problem [33].

. An integer linear programming problem (ILPP) to minimize the number of disjunctive constraints and a vector covering approach to reduce the number of the markings in FMSs is modelled with Petri nets. Further, the experimental results show that the proposed model can find optimal supervisors for these models that cannot be dealt with by the other works. But it has the computational complexity and also suffers from the state explosion problem [22]. The structured analysis to find the elementary strict minimal siphons (SMS) and the behavior of reachability graph techniques in FMS is modelled with Petri nets and investigated the relationship between the behavior and structures of the net. The simulation of the Petri Net is run on MATLAB environment and provided a system controller [51].

VII. CONCLUSIONS

Various and different studies related to complex issues involved in Flexible Manufacturing Systems have been solved both in terms of simulation models and experimentation using different techniques. The Flexible Manufacturing Systems being involved with concurrent, synchronization, mutual exclusion and conflict situations, the Petri Nets have been emerged as is one of the promising techniques that it can accommodate such characteristics very easily than that of other techniques. The various methods such as Reachability tree, Reduction technique, Iterative synthesis, invariant analysis etc., available in Petri Nets have been used to resolve different issues of FMS. Also the various traditional optimization techniques like; linear programming, integer programming, Genetic Algorithm, Artificial Intelligence, Heuristic search, Fuzzy logic etc., are incorporated into the Petri Net models. The related survey and review are brought-out pertaining to the usage of Petri Nets which have simplified the analysis and proved to be the best method for solving the problems of Flexible Manufacturing Systems.

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