INRIA

INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team COSTEAM

Optimal and secure management of manufacturing systems

Nancy - Grand Est

THEME NUM

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2. Overall Objectives

2.1. Overall Objectives

The COSTEAM project deals with optimal and secure management of discrete systems producing goods and services. Its main objectives are systems design, analysis and control.

Systems producing goods or services play a fundamental role in our economical environment which is facing major changes. In industrial production, the buzzword is no more productivity but capacity to react or agility. The preservation or the improvement of the competitiveness of an industrial or service system is strongly influenced by its environment, i.e. by the evolution of the market, by production technologies and by the people involved in its operations. Concerning the tomorrow's market, the economic studies are unanimous. The market evolves towards high-quality, low-cost products, of large variety (some even talk about personalized products or mass customisation) and renewed more frequently. It constantly evolves and becomes more and more difficult to predict. In such a very strongly competitive context, the performance of companies depends on their flexibility and their ability to react. The technological answer to this challenge relies on flexible and reconfigurable systems. A flexible manufacturing system has a high level of automation and uses sophisticated resources such as digitally operated machines, robots, etc. The amount of investments due to flexible systems requires a detailed preliminary study. Such a study requires a design phase comprising stages for modelling, analysis, performance evaluation and control synthesis of the future systems, even before these are settled. Their reconfiguration uses the same techniques to improve or adapt constantly these systems to the needs of the market. Due to the globalisation of economies, companies must be competitive in terms of costs, delays and quality. They must be flexible to meet the fluctuating demands and they must be reactive to face the exogenous and endogenous changes they undergo. More than ever they need rational tools and structured methods to better control the flows of products, information and decision, and to archive a better reliability of the production resources. The control of the whole supply chain, going from the suppliers to the consumers and encompassing all the stages of production, becomes a necessity. The objective of the COSTEAM project is to develop tools and methods which can help companies to design, model, evaluate and manage their production systems. More exactly, starting from industrial needs, we develop methods for modelling and evaluating performances, as well as associated tools and methodologies to help manufacturers to better design and manage their production systems of goods and services.

3. Scientific Foundations

3.1. Themes

Project COSTEAM addresses three complementary themes:

Theme 1: Performance evaluation and systems sizing.

The aim of this theme is to evaluate systems producing goods and services in order to design them or to provide them with efficient management and development strategies. Both generic optimisation methods dedicated to common systems and analytical and simulation methods dedicated to more particular systems are tackled.

Theme 2: Optimal control of system.

This theme deals with designing controllers for discrete event systems. The control synthesis of discrete event systems is addressed including time constraints and the uncontrollable/unobservable nature of some events. We pay a special attention to the notions of fault tolerance and recoverable systems in the case of industrial systems. The aim is to build the less restrictive control law which guarantees that the behaviour of the system respects given specifications.

Theme 3: Reliability and maintenance systems.

This theme deals with the development of efficient maintenance policies in the context of the production of goods or services under strong constraints. The proposed policies are developed by taking into account the production plan and the maintenance plan of the manufacturing system. The main challenge of these topics is the integration of modelling and optimisation techniques within a unified analysis process to design and to manage a complex system and then to synthesize its control. We give a special attention to modelling the maintenance activities, starting from the design phase of the manufacturing system.

These three presented thematic intend to provide systems producing goods and services, and more generally enterprise networks, with optimised strategies of control and development. For our case of studies, we do not consider isolated entities, but we take into account the relationships existing between the various partners. Two domains of application will be studied:

- **Industrial systems and services systems** (such as hospitals). We consider an entity that produces goods or services, taking into account complex constraints as well as interactions with its customers and its suppliers. We propose to develop both analytical methods and generic methods to optimise the behaviour of such systems.
- **Enterprise networks**. On the basis of models developed in the MACSI project, for this kind of application we study the operational management of the whole supply chain with respect to the organization, the monitoring and the optimisation of this supply chain. We also propose to consider e-procurement business subject to a certain amount of constraints within the framework of open markets via new technologies of information and communication.

3.2. Scientific Foundation

The performance evaluation and systems sizing aspect is very important for both application domains. Indeed, the research in this field is connected to the developments of discrete event systems. It is often caricatured by the rivalry between analytical methods and simulation. Some recent results allow to get rid of this rivalry and to make analytical methods and simulation complementary. Thus we develop analytical methods on the basis of simulation to evaluate and optimised systems producing goods and services. A new dimension in this research is the simultaneous consideration of the imperatives of production and the maintenance policies as well as the implementation of relevant indicators. Other research topics such as the study of hybrid systems (Discrete Event Systems and Continuous Systems) could be mentioned. In order to avoid dispersion of our research energy, these systems will not be approached on a short term but may be studied if the opportunity appears (i.e. industrial contracts) and if the human resource potential of the project allows.

COSTEAM project falls under the INRIA topic entitled "Numerical systems - Control and complex systems". It aims at proposing solutions and participating in knowledge advancement related to design, evaluation and management of discrete systems producing goods or services. The research goal is resolutely dual, giving top priority to fundamental research on one hand but always keeping in mind industrial applications on the other hand. On the short-term, we will thus focus on well-identified problems of design, performance evaluation, systems optimisation, maintenance policies definition, and also optimisation of e-procurement. Thanks to this experience, the aim on the long-term (5 years and more) is to develop a systematic method to design and analyse systems producing goods or services based on modelling and formal specifications of the structure and control of these systems, like software engineering does. The COSTEAM project takes benefits from the activities of the "Systémes de production (SdP)" team of the "Laboratoire de Génie Industriel et Production Mécanique" (LGIPM), common to ENIM, ENSAM-Metz and University Paul Verlaine of Metz. Most of its members belonged to the MACSI project of INRIA.

The COSTEAM project is built on concrete industrial needs which concern problems of design, management and optimisation of systems producing goods or services. Our research activity relies on conventional tools like operational research, Petri nets, perturbation analysis and others for solving problems encountered in designing and managing systems producing goods and services. These tools are the foundation for developing new methodologies more adapted to the industrial applications and the research challenges we are facing.

4. Application Domains

4.1. Application Domains

For a long time, only systems producing goods were studied with a lot of applications in the manufacturing world. More recently, systems producing services have been considered. These kinds of systems include

government services, banks, health services and hospitals, maintenance services, large distribution channels, etc. A common feature to these fields is their strong socio-technical component, the role of human beings remaining the driving force of these systems, throughout many functions (actor, decision-maker, operator, customer, etc). Thus it is very important to consider also these systems, by integrating new constraints (and more particularly the social, economical, technological and environmental ones), together with the complexity of the proposed systems with their human dimension. Therefore, the COSTEAM project tackles the study of critical problems of optimisation and decision-making existing in logistic systems, production systems and services systems. The goal is to evaluate, design and manage the following kind of systems:

Manufacturing systems such as:

- Discrete systems, existing for instance in the automotive industry, aeronautics or mechanical production;
- High-speed systems (with high rate flow of parts) or current flow systems that are very common in companies from various industrial sectors (e.g. food industry, pharmaceutics, cosmetics, electronics).

Services systems (government services, banks, health services, maintenance services, etc). The problems encountered are diversified. For instance, they can concern the definition of timetables; the design of planning's for maintenance agents travelling or the scheduling of working times for employees.

Logistic systems (supplying, production, distribution and transport), under their strategic, tactical and operational aspects. More specially, we are interested in:

- The logistical and industrial strategy and the problems related to location and sizing of logistic and industrial units;
- The scheduling and optimisation of supplying, stocks and distribution;
- The scheduling and optimisation of load transport, and more particularly long-distance transport by any way, combined transport and vehicles rounds, supplying transport, inter-factories transport and distribution.

Among all these domains, a new application field addressed in our team is the E-Procurement, which is a network of electronic management purchasing. Indeed, the emergence of new technologies provides manufacturing companies with new solutions to increase their competitivity. E-Procurement represents an effort from companies in their use of Internet to optimise their purchases using electronic trade through various ways, on-line services for calls for proposals, virtual market places, etc.

The Internet and the Web services allow companies to get over the geographical limits, to take benefits of a worldwide market and to build new relationships between customers and suppliers. A well-managed project based on E-Procurement is a major source of profits and reduction of administrative expenses.

However these technologies also bring new risks and weaken companies exploiting the worldwide market. This is the reason why one of the key factors for success is the capacity of companies to integrate an unstable relational framework, oscillating according to the object and the moment.

Studying the relationships customers-suppliers in the context of the e-procurement, integrating the E-Procurement into the optimisation of a purchasing program and taking into account risk factors (economical, social and environmental ones) are the main objectives of our research in this application field.

5. New Results

5.1. Performance evaluation and systems sizing

Keywords: *Distributed control*, *E-procurement*, *Green supply chain*, *Lagrange relaxation*, *Manufacturing systems*, *Metaheuristic*, *Multi agent systems*, *Petri net*, *Services*, *Simulation*, *Stochastic optimization*, *Stochastic systems*, *Supply chain*, *Traceability*.

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This part concerns the performance evaluation of critical problems. Setting up a new production system of goods or services, or modifying either the physical structure or the operation of an existing system, requires the system's performance to be evaluated and optimized.

5.1.1. Industrial systems and services systems

The first general subject concerns the scheduling of flexible systems (production or services) without storage capacity and with a specific blocking constraint encountered in many industrial processes. In classical blocking situations, a machine remains blocked by a job until this job starts the operation on the next machine in the routing. For the particular type of blocking constraints considered in our work, the machine remains blocked by a job until its operation on the downstream machine is finished (RCb constraint). Heuristics and genetic algorithms for solving these flowshop problems are developed and different initial populations are tested to find the best adapted [77], [78]. The metaheuristic called electromagnetism-like optimization heuristic (EM) developed to minimize the make span of Flowshop has been adapted to the hybrid Flow-Shop case. To solve the Job-Shop scheduling problem an exact method, new lower bounds and metaheuristic are proposed [41].

The impact of delays such as transportation, production or lead-times, is also studied in another aspect of our research program. The basic idea of this study is to develop an Infinitesimal Perturbation Analysis (IPA) for performance evaluation and optimization. Discrete and continuous flow models subject to time and operation dependent failures are defined taking into account these delays. The IPA technique was applied initially to queuing networks, where it reached the limits of its scope towards the end of the nineteen eighties. Subsequently it has been applied to stochastic flow models, where much of the action is today. Systems with delays hardly have begun to be investigated, and the few existing results indicate that the problem may become challenging, and the IPA derivative are more complicated than those that would be obtained for the system without delay. Thus, the main innovation of our research is in its explicit inclusion of delays in the model. Hence, the impact of these delays on the size of buffers are studied [81]. The control of the production systems with delays is also addressed and IPA is used for the continuous-flow model to optimize the production system [28], [75].

The type II assembly line balancing problem is also studied. This NP-hard problem consists in assigning assembly activities to a given number of workstations of an assembly line in order to minimize the cycle time subject to precedence constraints. Furthermore, we consider a new performance parameter which is the reliability of the line. This parameter represents the probability to respect the cycle time. First we considered that the reliability of the line is a constraint and we proposed an Electromagnetism based mechanism (EM) method to minimize the cycle time while respecting a given value of the reliability [88] [72]. Then we considered the reliability as a second objective function. We obtain a multi-criteria optimization problem where two objectives are considered simultaneously: i) minimizing the cycle time; ii) maximizing the reliability of the line.

Consequently, the aim is no longer to find an optimal solution, but to obtain a set of Pareto optimal solutions. It is well known that the computing time needed for an optimization method to converge depends on the quality of the initial solution. Therefore, we proposed a method to compute a lower bound for the initial solution. This problem is formulated as an integer linear program. The solution we propose is based Danzig-Wolf decomposition and column generation. The assembly line balancing problem with unreliable machines is considered in [68].

Another research domain we considered deals with the optimisation of production - distribution systems. We considered a multi-stage production-distribution system made up of production plants separated by warehouses. Customer orders arrive randomly to the finished goods warehouse according to a compound Poisson process. The quantity of each order is a random non negative integer variable and the quantities of different orders are iid random variables. First of all we developed an analytical approach to solve the optimization problem for a production-distribution system with two levels [27]. However, as the size of the

system increases, building an accurate analytical model becomes very difficult. Consequently, we proposed a simulation based optimization method to optimise the system when both the performance function and some constraints are evaluated by stochastic discrete event simulation [74]. We showed that, under some mild assumptions, the algorithm converge to a local optimum with probability 1.

Our research work concerns also service system control and engineering. First, we work on integrated method for teaching system specification [13] and control either by multi agent system [89] [67] or by a method in order to implement an integrated and reactive system of control. This method is composed of nine different steps from the definition of the system's strategy to the definition of the operational goals. The method is also using a phase of model to define a process map and a UML model. It is based on two principal activities: the deployment of the strategy through the conception of the performance measurement system and the conception of the control system itself. These two activities are articulated around a model activity, indispensable to implement our system [12], [29]. We work also on health field, specifically in a distributed environment [40], [45].

The advent of Internet and Internet-based technologies has led to new and innovative auction mechanisms for procurement. In e-sourcing, an industrial buyer procures its goods or services through online auctions from a set of pre-qualified suppliers. With the Internet technologies enabling an interactive front end for human interaction and back end computers that can support complex optimization algorithms, the research in e-procurement is focused on auction mechanisms, bidding languages, and winner determination techniques to make the process computationally and economically efficient. This has led to new generation of procurement techniques: volume-discount, combinatorial, and multi-attribute. Further, globalization and trade liberalization have pushed the companies to adopt integrated procurement strategies whereby national boundaries are discarded and factories from different countries are treated as from a single region.

In this area, our result concerns the discounts based on the total value of purchase which is a common business practice among the online retailers. The discounts offered could be in the form of rebates, cash backs, gift vouchers, or reward points. The comparison shopping bots provide only price information for individual items/products but do not consider the total value discounts that could be accrued by buying more products from the same retailer. In this work, we consider a buyer interested in buying M different items/products from N retailers that offer total value discounts. The buyer is faced with an optimization problem of choosing the retailers and the items/products to buy from them to minimize the total buying cost taking into account the total value discounts offered by the retailers. As results, an integer programming formulation for the problem, which can be integrated with the current comparison shopping search engines, is proposed. As this problem needs to be solved online, a linear programming based heuristic to obtain a near-optimal solution that could be used with the commercial solvers to accelerate the solution time, is developed [60], [43]. Extensive computational experiments are underway to study the time and space requirements for solving the problem by commercial solvers.

5.1.2. Case of supply chains

This subject concerns supply chains. We begin by the more classic logistic systems, and then move on to enterprise networks which are characterized by an extensive use of information technology.

Integrated supply chains are complex systems and their modeling, analysis and optimization requires carefully defined approaches/methodologies. Also, the complexities may vary greatly from industry to industry and from enterprise to enterprise. In contrast to traditional integrated supply chains, integrated long supply chains are more complex, with many parallel physical, information and financial flows occurring in order to ensure that products and/or services are delivered in the right quantities, with the requested quality to the right place in a cost effective manner at the right time. There is no generally accepted method by researchers and practitioners for designing, operating and evaluating agile integrated long supply chains. Therefore, our research work has attempted to investigate technologies, systems and paradigms for the effective management of long integrated agile supply chains. More specifically, a vision of the future technical issues and an insight into the future scientific and industrial advances required to meet future market and public demands are addressed. Two

developed approaches for modeling and evaluating agility in integrated long supply chains respectively *Fuzzy Intelligent based approach* and *Fuzzy association rules mining based approach* are developed [26], [59], [42].

Supplier selection with order splitting represents one of the most important functions to be performed by the purchasing department that determines the long-term viability of dynamic supply chains. As a second result, a novel approach for automatic knowledge acquisition, which clubs supplier selection process with order splitting for dynamic supply chains based on the attained knowledge from the variations in the market is developed. Moreover, the suggested approach imitates the knowledge acquisition and manipulation in a manner similar to the human schedulers who have gathered considerable knowledge and expertise in a given domain. As per this concept, those decision criteria for supplier selection are considered first, which are qualitatively meaningful like performance, service quality, innovation, risk etc. and thereafter their application is quantitatively evaluated. State variables are derived from the decision criteria to match the factors (flexibility, responsiveness, agility, position etc) associated with local competitive situation of the candidate supplier. Therefore, logically it can be inferred that the developed approach can generate decision making knowledge as a result, the developed combination of rules for supplier selection can easily be interpreted, adopted and at the same time if necessary, modified by supply chain decision makers/practioners [25].

In the next subject, we deal with the single vendor single buyer integrated production inventory problem. Two production strategies are considered for the vendor. The first one suggests that the buyer orders batches of size nQ and the vendor produces nQ and makes equal shipments of size Q. The second policy proposes that to satisfy the same ordered quantity, the vendor produces separately smaller batches of size Q, n times. Setup cost is adopted as the decision variable for the choice of the best strategy. The total average cost per time unit corresponding to each policy is considered as the performance criterion. The mathematical expressions of this cost are developed for each strategy and a computational procedure is used to determine a threshold value of the setup cost allowing choosing the best policy for any given situation. A generalized comparison between both strategies is proposed [53]. In [33], the choice between two single vendor single buyer integrated production inventory strategies is proposed. This work is made within the framework of a co-operation with professor Anis Chelbi.

Another research field concerns the distributed supply chain management. In most business and/or enterprise networks, each entity plans its own operations locally. Many reasons support this decentralized approach. Demand and supply information are widely spread within the networks, while there are continuous changes as the business environment is stressed by many internal and external factors, and finally the quantity of information to deal with is still too large in some networks to efficiently centralize the planning process. Moreover this decentralization raises some interesting questions which emerge from the difficulty to synchronize the planning and coordinate decisions without an extensive share of information as in a centralized approach. We work on a distributed approach, based on multi agent paradigm aiming to address this issue. Models based on Integer Linear Programming are developed in order to select best scenarios among subset of scenarios obtained by communication and negotiation between the various partners of the networks. First we deal with cooperative planning proposing a method to deal with contingency in supply chain [10]. Second we proposed a model describing entities behaviors [44], or multi-behaviors [39]. Finally, we have synthesized those works participating to a book redaction dealing with supply chain simulation [62], [61], [64], [63].

Green supply chain and intermodal transport are also considered in our research. The globalization of economy and the exchanges give birth to multi-site companies who own their own production centers and distributions centers, which distribute on great geographical areas. Since always, the distribution of products with various modes of transportation is not taken into account in the management of supply chain. On the contrary, it is the external service provider of the supply chain who always manages it, but it does not support the measurement of the performance to control the cost. The discounted growth of the goods carriage per mode in European Union would encourage the decision makers to take measures to limit their use of it and especially to limit their environmental impacts. Actually, in an era with more environmental conscience on a global level (Kyoto, Göteborg, etc.), the companies and service providers could no longer reject indefinitely on the community of environmental costs and will be, in all probability, subjected to heavy environmental tax in next years. The integration of the environmental and societal cost of transportation [83], [84] in the supply chain is rarely

quoted in the literature. This activity justifies the integration of the constraint in the model by the current state of environmental situation [35], the evolution of the legislation opposition to the problems generated by pollution (EURO 5 for European Union, for example), and the public pressure which is increasingly attentive with the environmental problems and the actions for reducing the pollution. We have also adapted multi-criteria methods AHP to our model [71].

Another research area for our team concerns the traceability within the agro-alimentary field. The starting point of this quest is the raw material dispersion optimization [52], criterion used subsequently for the determination of the criticality index of the production batches. From which we get to finally develop an optimization of the manufacturing products delivery in order to reduce the number of batches recalls in case of a crisis. This is achieved by using the decision-making aid, operational research and artificial intelligence tools [80].

5.2. Optimal control of systems

Keywords: *Air traffic management*, *Air traffic network*, *Discrete event systems*, *Fault-tolerant*, *Forbidden state problems*, *Forbidden state-transition problems*, *Optimal control*, *Supervisory control*.

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Our team has a reach experience on control synthesis for discrete event systems. The approaches we proposed allow solving the forbidden state problem and building a live maximal permissive controller. The existence of both uncontrollable and/or unobservable transitions is taken into account. However, we supposed so far that the controller cannot subject to any failure. In real systems, this is not the case, as the components of a real controller are not perfect. Electronic components may be subject to noise which can generate parasite signals and perturbations. Moreover, some commands may be lost during transmission. In order to overcome this problem we proposed a Petri net structure based on redundant controllers to reject a given number of faults. Two kinds of faults are considered: i) losing a token from a Petri net place of the controller; ii) getting an extra token in a Petri net place of the controller.

The solution we developed in [47] proposed a Petri net structure where n redundant controllers allow rejecting n-1 faults in a given fixed period of time.

Avoiding forbidden states by a supervisory control policy may lead to a non live system. In this work, we consider the problem of forbidden state specification for discrete event systems modeled by partially controlled Marked Graph (MG) in conjunction with liveness specification under control. Forbidden states are characterized by a set of General Mutual Exclusion Constraints (GMEC). The risk of deadlock on a closed loop control is proved and defined using the structural properties of marked graph. Therefore, a formal method to avoid the deadlock and guaranty liveness specification under control is developed in the thesis of Hatem SIOUD and its presented in [Sioud 08]. The deadlock problem is already presents else in control synthesis. In fact marked graph is well used for manufacturing modeling where marked graph represent the set of operation to do for each product and there is a resource places for these operations. In [85] the authors identify the deadlock causes in the output transition of critical places; they defined the controllable subnets related to these transitions. [93], present a formal method to solve the problem of deadlock. In their works, the authors defined subsets of resource places and transitions that can cause a deadlock and they called it the subset of deadlock. It proposes a formal method for to create control places to limit the number of token/resource, used by each one of these deadlock subsets. This work was developed in [51] This paper significantly extends the analytical results of [87] to a deadlock-free supervisor and provides simple analytical results for non-trivial cases of the GMEC specifications. More specifically, contributions and motivations of this paper with regard to [87] include:

1. It proves that deadlock free supervisor problem can be decomposed into two sub-problems; a control problem and a deadlock avoidance problem.
2. It significantly extends analytical results of [87] to deadlock free supervision for live marked graphs.

Taking into account the time information is crucial for realistic systems. This information can be used to compute more permissive control laws [90]. Time introduces a new dimension of considerable interest in DES control, but also of significant complexity. In a second work, we extend the results presented in [82] by considering time information. Each event has a fixed known duration. We design a simple optimal control law to guarantee that reachable markings respect the GMEC specifications. We discuss the influence of observability and time constraints on the controller synthesis and we show that the control law designed using time information is more permissive. Moreover, time information also enables us to relax the unobservability property for some transitions. Even if we cannot observe their execution, time information helps us to deduce their firing instant [34].

We apply the supervisory control on the air traffic management where it is necessary to have effective tools for decision-making aid to determine all acceptable configurations of the flight plans and then the optimal one. Based on the initial routes planning and taking into account the uncontrollable events; (climatic conditions, delay due to the breakdowns on the ground of some planes...) it is necessary to find a new acceptable and optimal configuration of the flight plans. This problem is dealt with according to a formalization in stochastic programming integrating the climatic constraints to find a new configuration of the flight plans [91], [92].

An air traffic system can be considered as a timed discrete events system. The problem of the air traffic management can be solved by using the syntheses method developed by COSTEAM group [86]. The aim of this work is to propose a flight plans which guaranteeing the respect of the specifications in terms of space temporal constraints while minimizing a function cost. Our proposed approach is based on the use of a Time Controlled Petri Net Model (see Figure 1), then we generate the Time Reachability Graph (see Figure 1) and we compute the best path (free forbidden state) and for which we have the best cost. This path represents the flight plans of each airplane.

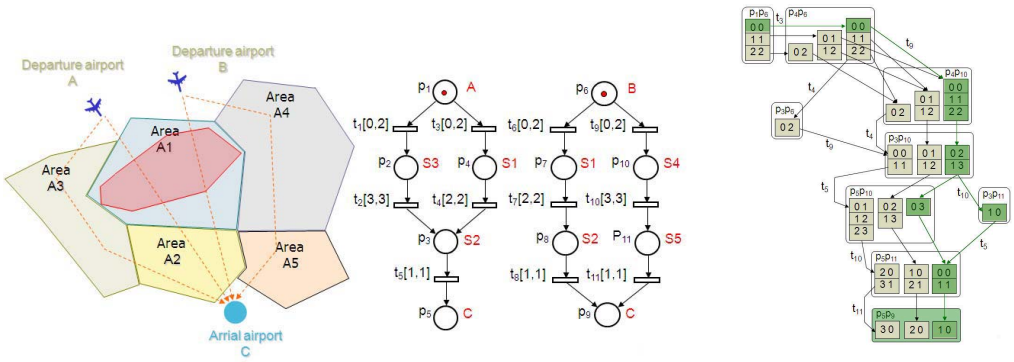

Figure 1. Time Controlled Petri Net Model of the air traffic and Time Reachability Graph.

5.3. Reliability and maintenance of systems

Keywords: *Average cost*, *Buffer stock*, *Corrective maintenance*, *Economical decision*, *Experimental design*, *Failure law*, *Inventory*, *Maintenance policies*, *Molds*, *Nonlinear mixed-integer programming model*, *Optimization*, *Performance*, *Preventive maintenance*, *Production planning*, *Profit*, *Prognosis*, *Quality control*, *Safety stock*, *Serial production system*, *Simulation*, *Subcontractor*, *Switching*, *Transport strategy*, *lot-sizing*.

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Generally, this theme concerns the optimisation of integrated maintenance policies for manufacturing systems. New integrated maintenance policies are developed and optimized in order to proof its performance according to the traditional policies existing.

Nowadays, the hard competition between the enterprises brings us to revise the currently adopted strategies of production and maintenance. In fact, the satisfaction of the client in time became a difficult spot since the randomly demand. Some approach related to this topic is developed in the PHD study of Mohamed Dahane. Dahane defended his thesis, directed by Nidhal Rezg, on November 2007. This thesis deals with the problem of subcontracting for petroleum transport companies. In this case, companies are providing subcontracting services by allocating the pipelines to other companies to meet a technical constraints (permanent use of pipelines) and to optimizing the pipelines' operation. Basing on analytical and simulation approaches we proposed a panel of integrated maintenance strategies in order to analyze the impacts of subcontracting. We studied the temporal impacts of subcontracting. We are interested in the effects of an unforeseen delay of beginning date and the duration of subcontracting. We developed analytical models to determine the optimal preventive maintenance period, the optimal size of the buffer stock and the impact of a delay or extension on the generated costs. After that, we deal with the problem of number of subcontracting to perform during one cycle. We analyzed joint production and maintenance policies for a system under a subcontracting constraint. The subcontractor system considered is comprised of one machine. Our objective is to satisfy a constant demand by building up a buffer stock in order to minimize the number of shortages that may occur during the periods of unavailability of the machine. We noted that these unavailability periods are caused by the machine failures and subcontracting periods. After each stage of stock accumulation, the machine is assigned to carry out subcontracting tasks. In the first part of this study, we presented an analytical model for the production maintenance policy. The second part tackled a generalized production maintenance policy which assumes that the machine can be assigned to subcontracting several times during a cycle. Some of strategies developed in Dahane thesis are presented in [17], [18], [19], [36]

More then, it's easy to note that the equipment state represents an important role in the quality control of produced items. Since that we focussed our work in the developing of a new maintenance integrated policy including the manufacturing system product quality aspect. This framework is more detailed in the PHD memory, of Mehdi radhoui [11], which is presented in April 2008. We are dealing in this thesis the integration problem between the various industrial components namely maintenance (preventive, curative maintenance, etc.), production (quantities to produce, stockpile size, etc.), and quality (rejection rate, non-compliances, etc.). To develop such integrated models Production - Maintenance - Quality, two approaches are adopted, the first is based on mathematical modelling and the second one uses simulation. As a first step, we propose to solve mathematically the problem sizing required for a production system that can randomly go to a state 'out of control' and produce nonconforming units. The system is subject to an age preventive maintenance policy. Once the transition to the state 'out of control' is detected, restoration actions are planned for L units of time later. A mathematical model was developed to found the economic production quantity Q and the age T for preventive maintenance. In a second time, we have developed joint policies of preventive maintenance and quality control for a production system that can generate conforming and nonconforming units. For the modelling of these strategies, we used two different approaches: the first full analytic and the second uses analytical tools and simulation. Each of the strategies proposed is based on a conditional maintenance. According to the rejection rate generated by the machine, one decides on the type of the maintenance action to undertake (preventive or overhaul). One of the assumptions on which we based modelling these strategies, assumed that after any maintenance actions (preventive maintenance or overhaul), the system returned to its original state (AS GOOD AS NEW). In another approach based on simulation, we propose to relax this assumption and assume that after the overhaul actions, the system returned to its original state (AS GOOD AS NEW), but after having undergone the preventive maintenance actions, the system is between its original state and his state just before the stop (between AS GOOD AS NEW and AS BAD AS OLD). It is interesting to note that the difference between the different approaches is presented in the method of integration of the quality aspect. In the first approach, the shift to the outside state control drives the entire strategy by the fact that maintenance activities are planned to L units of time later from that moment. While the second strategy is based on feedback, and no data of the equipment lifetime is known. It's the rejection rate which indicates

what kind of maintenance the system must undergo. The PHD study of Mehdi Radhoui, directed by Nidhal Rezg, is made within the framework of a co-operation with Professor Anis Chelbi from ESTT. The work of Mehdi Radhoui is presented in [15] In order to continue the efficient collaboration with Anis Chelbi, we treated a new study concerning the choose between single vendor single buyer integrated production inventory strategies [33]. The goal of this work is to establish an optimal integrated production and inventory policy for a single vendor single buyer system [53]. Another research work with Chelbi Anis, based on simulation approach and concerning the integrated inventory control with preventive maintenance policy, is developed [14]. In Other work with Chelbi Anis we have developed an integrated strategy of production control and preventive maintenance for a randomly failing production unit subject to a threshold required availability level [30].

In work with international partner, we have developed switching strategy in a subcontractor environment. The problem consists on a machine, unable to satisfy a constant demand since its unavailability periods. Point of view reliability, the machine is subject to random failures and its failure rate is increasing with its age and can be prevented by preventive maintenance actions. An age-limit policy is used for preventive maintenance planning and the machine stops for preventive maintenance when it reaches a given age. In order to satisfy the totality of the demand, the machine called upon to another machine, comprising the so-called subcontractor, which assures at a certain rate the same type of product. Two subcontractors can assure the rest of the demand. The two subcontractors have a different service cost and availability rate. In this a new strategy consisting at relaying on one of the two subcontractors and switching to the other at certain date. This strategy is justified and optimised analytically. The results of this study are presented in [37] and [38].

Since the success of this work, we proposed a prospect related to this study. More precisely we will consider several subcontracts; we recall that the last work is developed only for two subcontractors. The goal of this work is the developing of an optimal switching strategy between several subcontractors. More then, we will consider the building of a safety stock contrarily to the just in time strategy adopted before. In order to realize this future work we start a PHD study with Ayed Souheil. This PHD study is directed by the Professor Nidhal Rezg and co-directed by Dellagi Sofiene.

Other work has been developed with another international partner. With Cormier Gille we have developed a joint production planning of molds and end items, [16].

Currently, the contentment of the customer in time became a difficult spot. That's why it's interested to schedule an optimal production plan with taking into account the randomly demand and the manufacturing system performance. The objective is to reduce simultaneously the demand loss and the production cost. More then, it's easy to see that the manufacturing system degradation evolve according to the production rate. It means that the production plan has a direct influence on the manufacturing system failure rate. But the maintenance scheduling, with taking into account the failure rate evolution according to the production plan, is infrequently studied in literature. In order to develop the idea of the developing of the production plan and its influence on the manufacturing system degradation, we start a PHD study with Hajjej Zied. This PHD study will be directed by Nidhal Rezg and co-directed by Dellagi Sofiene. In the first part of this PHD study, we developed an optimal maintenance strategy combined with the production plan for a manufacturing system satisfying a random demand with taking into account the degradation of the machine according to the production rate. Thus, for a given randomly demand, we established an optimal production plan which minimizes the average total holding and production costs. Using this optimal production plan obtained and its influence on the manufacturing system failure rate, with an analytical study, we established an optimal maintenance scheduling which minimizes the average maintenance cost. The results of this approach are more detailed in the in [73]. Like prospects of this work and naturally the continuity of the PHD study of Zied Hajjej, with relaxing some assumptions used before, we will solve the problem using the linear quadratic Gaussian (LQG) control theory. After that we will take into account the demand rejection, and adapting subcontracting for the recycling of non-conforming products.

Another research has been developed in the FM (Fiability and Maintenance) field. In this research, we use the prognosis concept to develop a set of maintenance policies which integrate the schedule of the missions. The prognosis result is based on the evaluation of the degradation law, i.e. by taking into account the variations

of the environmental and operational conditions. The aim of this research is to determine the operating plan (scheduling missions) combined to an optimal maintenance plan. However, the missions performed by ships during an operating plan are various and the impact on the system is different. To model the failure law, we establish a relationship between the times between failure (from feedback) and risk factors of each mission. With the evolutionary failure law, the scheduling missions affect the reliability of the system, and we were whitebait to compare different maintenance policies [50]. In this research work, we have developed several preventive maintenance policies based on a dynamic failure law for a finite planning horizon. The dynamic failure law is used to adapt to various missions (characterized by environmental and operational conditions).The first preventive maintenance policy is periodic; the aim is to determine the number of maintenance activities to perform, in order to minimize maintenance costs. The effect of preventive maintenance is modeled by a reduction of the failure rate following the Arithmetic Reduction of Age (ARAinf). A mathematical model and a numerical procedure are developed to find the optimal number of preventive maintenance. Based on this policy, we sought the optimal business plan (ordered set of missions) [48]. In [49], we add a new decision variable to determine the optimal quality. For the second policy, which is sequential, the aim is to determine simultaneously the optimal number of preventive maintenance and these optimal lengths to satisfy the same economical objective. The optimal solutions are obtained by a numerical procedure [79]. The last (current) policy is based on a threshold of reliability to respect and we search the optimal reliability to obtain the number of PM and the lengths.

Another research program focuses on the development of models considering maintenance imperfections. Indeed, most preventive maintenance models assume that the system is restored to as good as new at each maintenance actions and consider the intervention time as negligible. Hence, the system may not be restored to as good as new immediately after the completion of maintenance action. Our approach is based on a fuzzy logic model which allows taking into account imperfections. These later are essentially due to technician's experience, the level of complexity of the restoration, and the time taken by maintenance actions. After a maintenance, the machine returns to an age between as good as new and as bad as old. Fuzzy logic is preferred over crisp logic because it is relatively easy to implement in this situation considering that the human factor is hardly interpreted by analytical methods because of its unpredictable nature. Simulation-based optimization is used to have a more reactive and accurate tool for parishioners. By taken into account the impact of the imperfections due to human factors, the period for the preventive maintenance, which minimizes the expected cost rate per unit of time or maximizes the availability of the system, is evaluated by a simulation-based optimization [22].

6. Other Grants and Activities

6.1. European projects

*6.1.1. Network of Excellence I*PROMS*

Participants: Zied Achour, Lyès Benyoucef, Sophie Hennequin, Vipul Jain, Nidhal Rezg, Alexandre Sava, Xiaolan Xie.

The Network of Excellence for Innovative Production Machines and Systems (I*PROMS: see http://www.iproms.org/: Innovative PROduction Machines and Systems; October 2004 - September 2009) is funded under the EU Sixth Framework Programme for a duration of five years. I*PROMS aims to address many of the challenges facing the manufacturing sector in the 21st century. It focusses research on intelligent and adaptive production machines and systems to realise its vision of the knowledge-based 'Autonomous Factory' for delivering increased competitiveness for manufacturing in 2020. Ultimately, this will help I*PROMS establish itself as the European Union's authoritative research body for the area of Production Machines and Systems.
At present, I*PROMS comprises 30 member institutions representing 14 European countries and the coordinator is Cardiff University (United Kingdoms)

To realise the 'Autonomous Factory' vision of I*PROMS, the Network will vigorously prosecute research in four integrated areas spanning the whole field of production equipment and technologies. These integrated areas, referred to as clusters, are 'core competency areas' and I*PROMS will invest the necessary finances and resources to support them. They comprise:

1. Advanced Production Machines (APM) Cluster: will research into the innovative and readily reconfigurable machines and systems and efficient manufacturing processes needed to deliver high-quality products competitively in the future.
2. Production Automation and Control (PAC) Cluster: will examine control issues associated with the 'Autonomous Factory' and the new ICT-based paradigms and algorithms needed to realise autonomy robustly and cost-effectively.
3. Innovative Design Technology (IDT) Cluster: will focus on activities that are traditionally upstream with respect to manufacturing and develop novel collaborative tools and techniques to bring design closer to manufacturing, thus producing gains in competitiveness through maximising concurrency.
4. Production Organisation and Management (POM) Cluster: will develop the innovative methodologies necessary to achieve manufacturing competitiveness. It will address the effective integration of human and technical resources. POM will create new sustainable management strategies for cost-effective and rapid reconfiguration of the Factory.

Members of COSTEAM contribute to clusters PAC and POM.

6.2. National and International Activities

6.2.1. National

- **ADENTS**

  COSTEAM and the entreprise ADENTS collaborates in the scope of the traceability management. Simòn Tamayo, PhD student, works with a "contrat CIFRE" in this context.

- **G2I center (Industrial and computer engineering center) - École Nationale Supérieure des Mines de Saint Étienne**

  Many collaborations exist with the G2I center and more particularly with Professors Xiaolan Xie and Alexandre Dolgui on the subjects of maintenance, control synthesis and logistics. Others collaborations related on the topics of scheduling and logistics are also on hand with Professor Stéphane Dauzère-Pèrès from the Department of Industrial Engineering and Logistics of Georges Charpak Microelectronics Center of Provence based in Gardanne.

- **LAGIS (Laboratoire d'Automatique, Génie Informatique et Signal) - École Centrale de Lille**

  Our team collaborate with Professor Étienne Craye, Manager of the SED (Systèmes à Événements Discrets) team of LAGIS, on the subject of controller synthesis for an application in the domain of reconfiguration.

- **LAI (Laboratoire d'Automatique Industrielle) - INSA Lyon (National Institute for Applied Sciences)**

  Professor Nidhal Rezg works in collaboration with Professor Eric Niel (manager of the team "Dependability and Monitoring of Industrial systems" of LAI) on the subject of control tolerating failures.

- **ORCHIDS (Operations Research for Complex HybrId Decision Systems) - LORIA - INPL**

  COSTEAM and Orchids collaborates in the scope of the supply chain manegement. Sma´l Khouider, PhD student of Orchids, is co-directed by Marie-Claude Portmann of Orchids and Thibaud Monteiro of COSTEAM[10].

- **SLP (Systèmes Logistiques et de Production) - IRCCyN**

  (Institut de Recherche en Communication et Cybernétique de Nantes)

  Professor Nathalie Sauer works in collaboration with the SLP team of IRCCyN, especially for which concerns management and development of production systems. She has also been ending the supervision of a PhD student of this lab whose thesis is related to evaluation and optimisation of event graphs.

6.2.2. International

- **Consortium FOR@C (de la FORêt AU(@) Client) - Canada**

  The staff of this project, and more particularly Dr. Thibaud Monteiro, work in collaboration with Dr. Sophie D'Amours (Manager for Research and Administration) and its team in the domain of collaborative management of enterprises in networks.

- **EAFIT University (Escuela de Administración, Finanzas y Tecnologías) - Medellin-Colombia**

  The staff of our project, and especially Dr. Sophie Hennequin and Professor Nidhal Rezg, collaborates with Professor Leonel Castanada of the laboratory GEMI - GRUPO DE INVESTIGACION ESTUDIOS DE MANTENIMIENTO INDUSTRIAL - at the EAFIT University in Medellin, Colombia, on the subject of developing expert systems for the maintenance of railway systems and power systems [69].

- **ESSTT (École Supérieure des Sciences et Techniques) - Tunis-Tunisia**

  The members of COSTEAM, and more particularly Professor Nidhal Rezg, collaborate with Dr. Anis Chelbi. This collaboration consists at undertaking research studies in order to develop new industrial integrated maintenance/production strategies with the aim of improving the traditional strategies.

- **ETSMTL (École de Technologie Supérieure) - Montreal-Canada**

  Professor Nidhal Rezg and Dr. Dellagi collaborate with Professor Ali Gharbi in the maintenance field.

- **FUCaM (Catholic university of Mons) - Belgium**

  The members of COSTEAM, and more particularly Professor Nidhal Rezg, collaborate with Dr. Fouad Riane (manager of the Center of Research and Studies in Industrial Management) in the field of alias management in hospitals. A PhD thesis started in September 2006 is being co-directed on this subject.

- **IIT (Indian Institute of Technology) - Delhi-India**

  India Since January 2007, Dr. Vipul Jain and Dr. Lyes Benyoucef are collaborating with Professor S. G. Deshmukh from the Department of Mechanical Engineering (IIT-Delhi) on the development of new approaches to address the issue of agility and lean in dynamic integrated supply chains.

- **ISB (Indian School of Business) - Hyderabad-India**

  Since May 2006, Dr. Lyes Benyoucef is collaborating with Dr. Kameshwaran Sampath from the Center for Global Logistics and Manufacturing Strategies (ISB-India) on the development of new techniques to solve some complex optimization problems present in E-Procurement environment.

- **RM "Reliability and Maintenance" Network - Canada**

  Partners of the RM network, the University of Laval (Canada), the Polytechnic School of Montreal (Canada), the Higher School of Science and Technology of Tunis (Tunisia) and COSTEAM, exchange their industrial and scientific experiences and results on reliability and maintenance of production systems.

- **Technological Institute of Celaya - Mexico**

  The staff of our project, and especially Professor Nathalie Sauer, collaborates with Professor Sergio Martinez (manager for research and development) on the subject of performance evaluation for

the management of complex systems. The officialising of this collaboration throughout a contract granted by the Mexican government is under consideration.

- **University of Quisqueya (Haïti)**

  COSTEAM and University of Quisqueya collaborates in the scope of the service system control and engeniering. Norly Germain, PhD student, works with a "co-tutelle" in this context.

- **University of Maryland - USA**

  Professors Xiaolan Xie and Nidhal Rezg have developed this collaboration all along the existence of the MACSI team. It concerns the optimisation of production systems subject to failures during maintenance operations. The technique used is based on performance analysis.

- **University of Moncton - Canada**

  Professor Nidhal Rezg, collaborate with Professor Gilles Cormier. This collaboration consists on developing new industrial integrated maintenance/production strategies.

7. Dissemination

7.1. Action for the research community

Most of the members of our project regularly participate in working groups of GDR-MACS (such as Bermudes, FL, RdP, CSP, INCOS, ORT, META, STP, GISEM) and Professor Nidhal Rezg is the leader of INCOS group (Control and supervision engineering of discrete event systems). The GDR-MACS has vocation to federate the community of the researchers in industrial engineering, by extremely interdisciplinary nature.

Many members of the team are members of the ROADEF (French Operations Research Society).

Didier Anciaux was the Chairman of the session entitled "Methodology of the design of systems of the production" of conference CPI'07 (Integrated design and production - November 2007) as well as special session "The durable supply chain" of conference MOSIM'08 (Modeling and Simulation - May 2008). Didier Anciaux was the initiator of the special session "The durable supply chain".

7.2. Member of program committees of journals or conferences

Professor Nidhal Rezg is member of the program committee of PENTOM'09 (Performance et Nouvelles Technologies en Maintenance) and IESM'09 (International Conference on Industrial Engineering and Systems Management). He is also guest editor of IJPR (International Journal of Production Research) and JIM (Journal of Intelligent Manufacturing).

Lyes Benyoucef was member of the international program committee for IEEE-CASE'08 (Conference on Automation Science and Engineering), ILS'08 (International Conference on Information Systems, Logistics and Supply Chain) and BS'08 (Business Sustainability). He is also editorial board member of IJBPSCM (International Journal of Business Performance and Supply Chain Modeling) and JOL (Journal of Operations and Logistics).

Sophie Hennequin has participated to the program committee of ISC'08 (Industrial Simulation Conference), which has been held in Lyon, France. She also participates to the reviewer committee of the CIE39 conference (International Conference on Computers and Industrial Engineering), which will be held in Troyes (UTT), France, July 6-8, 2009.

Members of the team are reviewers this year for the following journals: International Journal of Advanced Manufacturing Technology, IEEE Transactions on Automatic Control, Computer and Education, International Journal of Production Research, Decision Support System, Discrete Event Dynamic Systems, Journal Européen des Systémes Automatisés, Discrete Optimization, and for the following conferences: ECC'08 (European Computing Conference), ISC'08 (Industrial Simulation Conference), IMETI'08 (International Multi Conference on Engineering and Technological Innovation), MOSIM'08 (Modélisation et Simulation), ACC'08 (American Control Conference).

Members of the team have organized with the LGIPM (Laboratoire de Génie Industriel et Production Mécanique) the days " Journées Sciences et Techniques de la Production de Biens et de Services du GDR-MACS " which took place on November 20th and 21st and which grouped together 200 researchers.

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