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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 environnement 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 reconfigurative 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 achive a better reliability of the production resources. The control of the whole supply chain, going from the suppliers to the consumers and emcompassing 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. Scientific Foundations

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 topics intend to provide systems producing goods and services, and more generally enterprise networks, with optimised strategies of control and development. For our case 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.

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 optimise 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 Continous 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 producig goods and services. These tools are the foundation for developing new methodologies more adapted to theindustrial 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 plannings 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 supplyings, 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-Procu-rement, 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 suplly 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 new 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). In the Flow-Shop case, a new metaheuristic called electromagnetism-like optimization heuristic (EM) has been developed to minimize the makespan [66]. An exact method, list methods and lower bounds have been proposed to solve the Job-Shop scheduling problem [56].

Another component of our research program has dealt with the development of models with discrete or continuous flows subject to time and operation dependent failures. The majority of models do not take into account delays (production, lead-times and transportation) which have a great impact on performance measures and optimisation. Hence, the modelling and the impact of these delays on the throughput rate are explicitly studied. The control of the production systems with delays is also addressed and the Infinitesimal Perturbation Analysis technique is used for the continuous-flow model to optimise the production system [30], [31], [69], [87].

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. In a first step stochastic operation times for each assembly activities are considered and a new methodology electromagnetism- like mechanism (EM) is used to solve this stochastic problem [59], [81]. A new heuristic is also outperformed for large scaled problems [57] and estimation of distribution is also defined for the non-stochastic type II assembly line balancing problem [58].

Our research work deals also with the optimisation of serial multi-stage production - distribution system made up of production plants and warehouses for finished goods or semi-finished goods. Only one type of products is considered through the system. 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. Each warehouse is controlled according to a base stock inventory control policy and generates replenishment orders to its upstream plant. At first we developed an analytical approach to minimize the inventory cost for two stages production distribution system made of a warehouse supplied by a production facility. The analytical model is accurate for a two stages production-distribution system [85]. However, as the size of the system increases, building an accurate analytical model becomes very difficult. Therefore we built a simulation based optimisation method to be used when both the performance measure and some constraints of a multi level production-distribution system are estimated via stochastic-discrete event simulation. This method is based on random search in a neighbourhood structure called the most promising area. We show that under some assumptions, the algorithm converges to a set of local optimal solutions with probability 1 both when the solution space is bounded or unbounded. We also show that the local optimal solution is the best between the simulated ones [67], [86]. This approach is applied to cost optimisation of a production-distribution system subject to fill rate specifications. Furthermore we focus our attention to production-distribution systems where the production facilities are not reliable.

A new theme of our research concerns the production system of goods or services. The objective is to optimize in the same time conception and control decision in learning institutes. Indeed, we propose engineering methods to processes specification [10], [45], model and control [28], [88], [89]. We use analytical methods to generate solution for control and conception. We develop models to performance evaluation of those learning institutes [71].

Another research field concerns the design of stochastic distribution networks using lagrangian relaxation and simulation based optimization. The first and the second results address the design of single and multi-

commodity distribution networks, where a single supplier is serving a set of retailers through a set of Distribution Centers (DCs) to locate. The number and location of DCs are decision variables and they are chosen from the set of retailer locations. To manage inventory at DCs, for each commodity, the Economic Order Quantity (EOQ) policy is used by each DC, and a safety stock level is kept to ensure a given retailer service level. Each retailer faces a random demand and the supply lead-time from the supplier to each DC is random. The goal is to minimize the total location, shipment, and inventory costs, while ensuring a given retailer service level. We develop a novel Lagrangian relaxation based approach to solve the two problems. Furthermore, we conduct some computational experiments and analysis to show the effectiveness of the proposed approach [37], [73]. The third result deals with the design of production-distribution networks including both supply chain configuration and related operational decisions such as order splitting, transportation allocation and inventory control. The goal is to achieve the best compromise between cost and customer service level. An optimization methodology that combines a multi-objective genetic algorithm (MOGA) and simulation is proposed to optimize not only the structure of the production-distribution network but also its operation strategies and related control parameters. A flexible simulation framework is developed to enable the automatic simulation of the production-distribution network with all possible configurations and all possible control strategies. To illustrate its effectiveness, the proposed method is applied to a real life case study from automotive industry [23].

Recent trends are focusing on user friendly Business-to-Business e-procurement applications that embed sophisticated business logic and algorithms. With the Internet technologies enabling an interactive front end for human interaction and back end computers that can support complex computations, the research in e-procurement is focused on auction mechanisms, bidding languages, and bid evaluation techniques to make the process computationally and economically efficient. This has led to new generation of procurement techniques: *volume-discount*, *combinatorial*, and *multi-attribute*. Discount auction is a procurement mechanism for buying M indivisible heterogeneous items. The bidders are suppliers and a bid consists of two entities: individual cost for each of the items and a non-decreasing discount function defined over the number of items. The winner determination problem faced by the buyer is to determine the winning suppliers and their corresponding winning items that minimizes the total procurement cost, subject to the supply, demand, and discount constraints. As a new result, we show that this problem is $\mathcal{NP}$-hard upon reduction from the set covering problem. Moreover, we develop an integer programming formulation and derived some valid inequalities, which serve as cuts to the linear relaxation. A collection of branch-and-cut algorithms are developed with different cut addition techniques and branching strategies. The performance of the proposed algorithms for different problem types are demonstrated with extensive computational experiments [27].

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.

In this first subject, we propose two new approaches to model and evaluate agility in integrated supply chains. The ability to build lean and agile supply chains has not developed as rapidly as anticipated, because the development of technology to manage such concepts of lean/agile for integrated supply chains is still under way. Also, due to ill-defined and vague indicators, which exist within leanness/agility assessment, many measures are described subjectively by linguistic terms, which are characterized by vagueness and multi-possibility, and the conventional assessment approaches cannot suitably nor effectively handle such dynamic situations. As a new result, firstly, we propose a novel approach to model agility (which includes leanness) and introduce *Dynamic Agility Index* (DA_{Li}) through fuzzy intelligent agents. Generally, it is difficult to emulate human decision making if the recommendations of the agents are provided as crisp, numerical values. The multiple intelligent agents used communicate their recommendation as fuzzy numbers to accommodate ambiguity in the opinion and the data used for modeling agility attributes for integrated supply chains. Moreover, when agents operate based on different criteria pertaining to agility like flexibility, profitability, quality, innovativeness, pro-activity, speed of response, cost, robustness etc. for integrated supply chains, the ranking and aggregation of these fuzzy opinions to arrive at a consensus is complex. The proposed fuzzy intelligent agents approach provides a unique and unprecedented attempt to determine consensus in these

fuzzy opinions and effectively model dynamic agility. The efficacy of the proposed approach is demonstrated with the help of an industrial real life case study [26], [62].

There is no generally accepted method by researchers and practitioners for designing, operating and evaluating agile supply chains. Therefore, as a new result, secondly, we develop a new approach based on Fuzzy Association Rule Mining to support the decision makers by enhancing the flexibility in making decisions for evaluating agility with both tangibles and intangibles attributes/criteria such as Flexibility, Profitability, Quality, Innovativeness, Pro-activity, Speed of response, Cost and Robustness. Also, by checking the fuzzy classification rules, the goal of knowledge acquisition can be achieved in a framework in which evaluation of agility could be established without constraints, and consequently checked and compared in several details. Efficacy and intricacy of the proposed approach for finding fuzzy association rules from the database for evaluating agility is demonstrated with the help of an illustrative industrial real life example [24], [61].

In the second subject, we deal with the single vendor single buyer integrated production inventory problem [75], [76]. 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 also 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 [29], [84]. Second we proposed a model describing entities behaviors [64], [68], [83]. Finally, we have synthesized those works participating to a book redaction dealing with supply chain simulation [14], [18].

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 cost of transportation [40], [41] 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, 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 [39], [79]. We have also adapted multi-criteria methods AHP and ELECTRE to our model. AHP is efficient to exclude the incompatibility

and indifference between alternatives but its performance is not consistent for decision judgment; while ELECTRE escapes the procedure of determination of intrinsic parameters but it accepts the incompatibility and indifference between alternatives [38], [55], [77].

A new research area for our team concerns the traceability within the agro-alimentary field. Thanks to a preliminary bibliographical study [78], the starting point of this quest is the raw material dispersion optimization [91], 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 [92]. Another research activity concerns the identification of some new strategies and challenges in dynamic supply chain procurement activities for the future. In fact, to identify the complexities, gaps and challenges associated with the dynamic supply chain procurement activities, an exhaustive literature review is conducted. More specifically, the literature is examined from perspectives of the supplier related issues especially supplier selection process and supplier-buyer relationships existing in dynamic supply chain at both operational and strategic levels. As a new result, emerging issues and challenges resulting to scope for future works on supply chain procurement activities are identified and some clear guidelines for future research in this area are proposed [44].

Since a single supply chain configuration will neither be optimal nor efficient under dynamic and uncertain conditions, where objectives may conflict, the issue of dynamic configuration of supply chains needs serious research attention. As a new result, we combine a high level petri net with probabilistic reasoning as probabilistic petri nets to model a Multi-agent system (MAS) and detecting together goal and plan conflicts dynamically and concurrently for supply chain networks. We model supply chain dynamics based on conflicts. An integrated framework to tackle conflicts includes two stages: Conflict Recognition (CR) and Conflict Investigation (CI). CR module acts as a monitor to dynamically detect different conflicts; once conflicts identified, conflict investigation module is triggered to evaluate and rank the conflicts, which indicates to what extent the conflict will impact the agent's behavior. The model explicitly captures the interactions among supply chains and within supply chains [60].

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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The problematic of optimal control is a subject which keeps a great interest and involves many questions. The optimal control aims at defining a supervisor or an optimal controller using a reliable synthesis method. Our controller synthesis approach is based on the regions theory initiated by Badouel and Darondeau [93].

Regarding the control synthesis, a certain amount of original results have been proposed, such as control synthesis based on the use of theory of regions. The problems considered were initially from type "forbidden states" with the hypothesis that some events of the discrete event system to be controlled should be uncontrollable or unobservable. This study led to the design of two separate approaches for a problem of forbidden state transition even more general than the problem of forbidden states.

The first approach allows building a controller with places of Petri net [97], [94] (called Petri net controller), starting from the Petri net model of the system to be controlled and the specification of the expected behaviour. The model to be controlled is very common but it is bounded. The synthesis of control places is based on the use of regions theory. The synthesis approach of Petri nets controller using the theory of regions concerns a larger class than the one related to problems of forbidden states; this is the class of problems of forbidden state transitions (FSTP). In a FSTP, a transition between states can be undesirable even if the state it creates is not forbidden. In these problems, when a control through Petri nets exists, it is determined by the approach. The control places can be pure or unpure. Moreover, the control well defined is maximum permissive, i.e. the system controlled exactly owns the expected behaviour. The synthesis of control places requires enumerating all the admissible states. The case when no Petri net controller exists is defined by necessary and sufficient conditions. It then follows some sufficient conditions in terms of places marking of the model.

Our researchs in control synthesis are declined into three main works: The first job concerns the problem of non-existence of controllers. Indeed, it is not always possible to find a solution through places when a supervision problem is concerned. We have worked on the existing conditions of controllers in terms of places. Considering the cases when the Petri net controller maximum permissive does not exist, we have set up a new class of Petri nets for which the necessary and sufficient conditions for the existence of Petri net controllers are always true. It is the class of Petri nets essentially safe. To solve a problem of forbidden state transitions related to a basic Petri net model and for which there exists no Petri net controller, we suggest to modify the associated model into a network essentially safe, and then to apply our approach based on the theory of regions. This solution involves a growth in the size of the reachability graph due to the modification of the Petri net model of the plant. Our goal is to minimise the complexity in order to find a controller based on Petri nets places and that the transformation made it possible to help to solve the problem without touching with the characteristics and the properties of the initial Petri Net model of the plant. The second job concerns the consideration of time aspect. This job is strongly justified by the lack of formal synthesis methods to specify time control. These specifications reveal for instance constraints in the execution of tasks within time windows. This aspect is not easy to consider since it involves problems of process modelling and control specifications including time. The objective is to develop a formal synthesis method for time specifications and also for specifications such as expected sequence [13], [36]. The third job concerns the development of optimal controllers tolerating software errors of the control system. The fault tolerance is important during the design step of the controller for a discrete event system. We will consider control faults and we will try to set up covering procedures to avoid violating security specifications. These procedures allow discrete event systems to tolerate control faults. The generation of these procedures will be based on formal synthesis methods. This way, the synthesized controller will be sure and optimal, in the sense of the number of visited states, while avoiding the forbidden states defined in the security specifications.

We apply the supervisory control on the air traffic management where it is necessary to have effective tools for decision-making aid to determine the acceptable configurations and then optimal one of the flight plans. On the basis of 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. [95], [96]

An air traffic system can be considered as a timed discrete events system. The problem of the air traffic management can be solved by the generation of a sure and optimal supervisor. This supervisor is optimal in terms of cost of the air traffic management. Therefore, our objective is to propose supervisors guaranteeing the respect of the specifications in terms of space temporal constraints while minimizing a function cost. It is important that the supervisor is most permissive to explore the maximum of possibilities of the routes reconfiguration. Air traffic management is a new topic of research and we want to collaborate with the group air traffic management of the University of Washington

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.

Since the hard competition lived by the actual enterprise. The satisfaction of the client in time became a difficult spot. Since that, the majority of the actual company calls upon to the subcontractor in order to cover the client demand and to reduce the demand loss. In fact, it's time to expand new integrated maintenance production strategies by taking into account the context of subcontractor. Since that, we treat some maintenance policies integrated with production under the subcontractor constraint. Since that, we elaborated different strategies integrating maintenance and production. In these strategies we are taking in account the constraint of subcontractor. These strategies are optimized and its performances are compared analytically and by simulation to a simple maintenance policy actually adopted by the enterprises. Some of these policies are developed and proved in [21], [53], [51]. More precisely, in [21], [53], [51], the manufacturing system under consideration consists on a basic machine which produces a single product. In order to satisfy a constant demand, the system called upon to subcontractor. The subcontractor is presented by a second machine which produces at a certain rate the same type of product as a basic machine. Both machines are subject to random failures. An age-limit policy is used for preventive maintenance of the basic machine. Point of view maintenance actions, the subcontractor is not controlled by us. We considered that the subcontractor imposes some unavailability periods. That's why we suppose that the failure rate of the subcontractor is constant. In this work we elaborated different strategies integrating maintenance and production. In these strategies we are taking in account the constraint of subcontractor. These strategies are optimized and its performances are compared to a simple maintenance policy in which we don't taking in account the subcontractor. Finally, we classified all the strategies developed in this work according its performances orders compared to the simple maintenance policy and noted the performance constraints of theses policies. Another vision of the subcontractor is described in [20], in which the authors developed efficient policies of maintenance and control in a subcontracting environment in a context of just in time. This study, inspired from an industrial problem, is undertaken according to two orientations. The first relates to the call to subcontracting in the objective to satisfy a customer demand knowing that our system of production cannot satisfy the totality of the demand. The second orientation places our production system as supplier. For first orientation, we consider a production system composed by a basic machine which must satisfy a constant demand. For that, this machine calls upon subcontracting to ensure the totality of the demand. Subcontracting is represented by a second machine with a constant failure rate. Three maintenance policies for a basic machine are tested and evaluated. For the second orientation, we deal with problem of production and maintenance under constraint of providing subcontracting. We consider a production system made up of two machines with random laws of breakdowns. Two machines produce only one type of product and feed a stock of finished capacity to satisfy a constant demand. The machines can be allocated to carry out tasks of subcontracting. The objective of this part of article is to prove the efficient of integrated maintenance policy, making the coupling between the control and the management of maintenance in a subcontracting environment.

Another approach related to this topic is developed in the PHD memory of Dahane which will be presented in November. In this memory, Dahane studied the problems generated by the integration of subcontracting activity in a pipeline companies, providing subcontracting services for the petroleum products transportation. He identified the conditions of profitability of subcontracting and we study different manners to release the requested tasks of subcontracting, and he studied the impacts of an unforeseen extension or delay of subcontracting on the generated costs. The important results of this memory are presented, justified and proved by numerical examples in [19], [48], [49], [47], [50].

In the same aspect, we have compared two strategies for operating a production system composed of two machines working in parallel and a downstream inventory supplying an assembly line. The two machines, which are prone to random failures, undergo preventive and corrective maintenance operations. These operations with a random duration make the machines unavailable. Moreover, during regular subcontracting operations, one of these machines becomes unavailable to supply the downstream inventory. In the first strategy it is assumed that the periodicity of preventive maintenance operations and the production rate of each machine are independent. The second strategy suggests an interaction between the periods of unavailability and the production rates of the two machines in order to minimize production losses during these periods. A simulation model for each strategy is developed so as to be able to compare them and to simultaneously determine the timing of preventive maintenance on each machine considering the total average cost per time unit as

the performance criterion. The second strategy is then considered, and a multi-criteria analysis is adopted to reach the best cost-availability compromise. This work is made within the framework of a co-operation with Professor Anis Chelbi [16].

More then, since that the equipment state plays an important role in controlling quality of produced items, we developed a maintenance integrated policy including the quality of the manufactured product as a reliable indicator. This indicator will then allow building analytical models for maintenance and control. This quality indicator will also be able to take into account the impact of human skills in the efficiency of maintenance operations. We will thus consider the integration of human skills in the management of maintenance policies. In fact in this track, we develop a joint quality control and preventive maintenance policy for a production system producing conforming and nonconforming units. The results of this approach are detailed in the in [32], [33], [70].

In work, we have developed transportation strategy selection in a subcontractor environment. The problem consists on a transport enterprise, unable to satisfy a constant demand since its unavailability periods. These unavailability periods are reduced by applying preventive maintenance actions. Since this situation, the transport enterprise called upon to another transport enterprise, comprising the so-called subcontractor transport enterprise, which assure at a certain rate the transport of the same type of product. In order to assure an economical objective, the transport enterprise has a choice between two subcontractors having some different data. We have proved analytically in this work that the choice of the subcontractor enterprise is conditioned by the unit loss cost due an unsatisfied demand of one product. A numerical example and a sensitivity study presented in [52] confirm the analytical result.

In work with international partern, 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 't'. This strategy is justified and optimised analytically. The results of this study are presented in [80].

In another research work, fuzzy logic is used to model the impact of human behaviour in the preventive or corrective maintenance actions. 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. However, for most repairable systems, the maintenance action is not necessarily the replacement of the whole system, but is used to slow the rate of system degradation and increase the lifetime. Hence, the system may not be restored to as good as new immediately after the completion of maintenance action. This is why consideration of maintenance imperfections and modelling of these imperfections is important for developing a more accurate maintenance program [42], [43], [82]. We also use fuzzy logic to define a decision making for products subcontracting taking into account maintenance actions. Indeed, when deciding to use subcontracting for the manufacturing of products, the industry usually focuses on its production capacity and forgets to take into account the effects of its maintenance actions. Then, the purpose of this work is to present a method where the closeness to the next maintenance action as well as the production capacity is taken into account to make the subcontracting decision. This method is based on fuzzy logic as it simplifies the decision making when having to analyze the effects of the amount of parts to deliver, its deadline and the closeness of the next preventive maintenance action [54].

We have developed another work on integrated strategy of production control and preventive maintenance for a randomly failing production unit subject to a minimum required availability level. The production unit is submitted to a maintenance action as soon as it reaches a certain age or at failure whichever occurs first. A finite buffer stock is built up at time 'A' from the start of a production cycle in order to guarantee a continuous supply of the subsequent production unit at a constant rate during repair and preventive maintenance actions

whose respective durations are random. A mathematical model and a numerical procedure are developed to find simultaneously the optimal values of the preventive maintenance age, the stock level and the building time 'A' which minimize the total average cost per time unit and satisfy the availability constraint. The results of this analytical work is presented and commented in [35].

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 [90]. For each possible operating plan, we were optimal whitebait to determine the dates for maintenance that minimize maintenance costs.

Other work has been developed with another international partner. This work develops, based on an actual case study, simulation and mathematical modelling frameworks for simultaneously generating production plans for molds and the end items to be made with them. Any shortfall in molds has negative repercussions on the ability to meet promised item due-dates, thus justifying a coordinated production planning approach. Some of the inputs considered are item demand, holding costs, shortage costs and ordering costs, as well as the statistical lifetime distributions (in terms of number of uses) of the molds. This work is made within the framework of a co-operation with Professor Gilles Cormier [46].

6. Other Grants and Activities

6.1. European projects

*6.1.1. Network of Excellence I*PROMS (Innovative PROduction Machines and Systems; October 2004 - September 2009)*

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/) 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 (UK)
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 contribuate to clusters PAC and POM.

6.2. National and International Activities

6.2.1. National

- **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.
- **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.
- **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.
- **LAGIS (Laboratoire d'Automatique, GÃ©nie 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.
- **ORCHIDS (Operations Research for Complex HybrId Decision Systems) - LORIA - INPL**

  In the scope of the supply chain management, SmaÃ¯l Khouider, PhD student of Orchids, is co-directed by Marie-Claude Portmann of Orchids and Thibaud Monteiro of Costeam.
- **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.

6.2.2. International

- **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 officializing of this collaboration throughout a contract granted by the Mexican government is under consideration.

- **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.

- **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.

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

  The members of COSTEAM, and more particularly Professor Nidhal Rezg, collaborate with Dr. Fouad Riane (manager of the Centre 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.

- **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 INVESTIGACIÃN ESTUDIOS DE MANTENIMIENTO INDUSTRIAL - at the EAFIT University in Medellin, Colombia, on the subject of developping expert systems for the maintenance of railway systems and wind turbines.

- **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.

- **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.

- **University of Moncton - Canada**

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

7. Dissemination

7.1. Scientific community animation

7.1.1. Action for the research community

Most of the members of our project regularly participate in working groups of GDR-MACS (such as Bermudes, Vendôme-OGP, 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).

7.1.2. Member of program committees of journals or conferences

Sophie Hennequin participates to the program committee of the SAUM07 conference (IX Triennial International SAUM Conference on Systems Automatic Control and Measurements), which has been held In Nis, Serbia, November 22-23, 2007.

Members of the team are reviewers this year for the following journals: IEEE Transactions on Automatic Control, Computer and Education, International Journal of Production Research, Decision Support System, Discrete Event Dynamic Systems, Journal Européen des Systèmes Automatisés, Discrete Optimization, and for the following conferences: MOSIM08, ACC2008, CIE 37 (the 37 th International Conference Of Computers and Industrial Engineering).

7.2. Teaching

Teaching activities are located at the University of Metz (UFR MIM) and at École Nationale d'Ingénieurs de Metz.

Nathalie Sauer is responsible of the Master X-AP (University Paul Verlaine - Metz) and is responsible of the Department of Industrial Engineering and Maintenance (IUT Thionville).

Nidhal Rezg is responsible of the Master Gestion et Organisation Industrielle (University Paul Verlaine - Metz).

Didier Anciaux is responsible of the Licence Professionnelle Gestion de la Production Industrielle (University Paul Verlaine - Metz).

Alexandru Sava is responsible of the option Quality (École Nationale d'Ingénieurs de Metz) and co-responsible of the Master Logistique et Qualité (École Nationale d'Ingénieurs de Metz).

Sophie Hennequin is co-responsible of the option Research and development (École Nationale d'Ingénieurs de Metz) and responsible of the option International Project Management which takes place in Almeria (Spain) (École Nationale d'Ingénieurs de Metz).

Thibaud Monteiro is in charge of the Licence Professionnelle Gestion de la Production Industrielle (University Paul Verlaine - Metz).

Many members of COSTEAM give courses within the research Master Conception, Industrialisation et Innovation of Metz (Sophie Hennequin, Nidhal Rezg, Nathalie Sauer).

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