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A Life Dedicated to the Science, Philosophy and Romanian Society

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Mihai Drăgănescu

With outstanding contributions in Electronics, Informatics, and Philosophy, and as Professor, Researcher, and Manager, Acad. Mihai Drăgănescu is the most important encyclopedic personality of contemporary Romania.

Educated in the nascent Romanian school of electronics, Acad. Mihai Drăgănescu creates a world-class school of electronic devices and microelectronics. Envisioning the evolution of the modern society, becomes initiator and promoter of the informatics revolution in Romania, conceptually defining it and coordinating its development. Generalizing the concept of information, creates an original philosophy that leads to the development of a new type of science, called structural-phenomenological, with major implications for the understanding of the world and its future. First president of the Romanian Academy renaissance, he leads both its return to its role and traditional sources, and its renewal and adaptation to the evolution of the civilization. Promoter of the scientific and humanistic culture, brings back the deserved recognition to major personalities of the Romanian spirituality. Mentor and life model, he lightens and encourages many young generations with an extraordinary generosity.

Any of these achievements would be enough to place Acad. Mihai Drăgănescu among the greatest Romanian personalities. Their combination, impressive through their diversity and unity, creates the image of a personality of a rare complexity and creativity.

1 Founding Father of the Romanian School of Electronic Devises and Microelectronics

Acad. Mihai Drăgănescu was educated as an electronics engineer, and climbed through all the professional levels, from assistant professor to academician. Despite the unsupportive research environment of an isolated Romania, he succeeded in obtaining truly outstanding results. At the beginning of his scientific career, as a young assistant professor, Mihai Drăgănescu is among the very few Romanian electronics engineers with world-class research results, author of the first Romanian PhD in the area of electronic devises, entitled "The Capacities of Electronic Tubes and Their Dependence of the Functioning Conditions". This is followed by other fundamental research results, such as the Matz-Drăgănescu theory of the transistor at high-level of injection, the study of the inductive effects in semiconductor devices, and the simplification of the dielectric diode theory. They represent the prelude of "*Electronic Processes in Semiconductor Devices of Circuits*" [1], one of the first authored books in this domain in the world and an exceptional achievement in the Romania of 1962, recognized with the State Prize. In 1963 he publishes the first Romanian study on Microelectronics [2], and is awarded the Prize of the Ministry of National Education for his scientific research. He establishes and heads the Research Institute for Electronic Components, in 1969, and teaches the first course on Integrated Circuits, in 1970. In 1972 he publishes "*Solid State Electronics*" [3], the second fundamental book of the Romanian School of Electronic Devices.

A unifying understanding of Electronics, Informatics and Philosophy, in a social context, leads Prof. Drăgănescu to the development of a basic discipline of the science and technology of information, which he calls "Functional Electronics". In 1978 he starts teaching this new discipline at the 'Politehnica' University of Bucharest. Then, in 1991, he publishes the book "Functional Electronics" [4], followed by several studies, including "Microelectronics and Functional Electronics" [5], "From solid state to quantum and molecular electronics, the deepening of information processing" [6], and "Neural Engineering and Neural Electronics Facing Artificial Consciousness" [7].

In an activity spanning almost 50 years, through original research, the publication of world-class foundational books, the development of new courses, the formation and support of a large number of specialists, the guidance of the Romanian industry of electronics and computers, including the management of the manufacturing of the integrated circuits, Acad. Mihai Drăgănescu has created the Romanian School of Electronic Devices and Microelectronics, significantly influencing the evolution of the Romanian society.

As an international recognition of his exceptional contributions, Acad. Mihai Drăgănescu is elected Fellow IEEE in 1994, Life Fellow IEEE in 1997, and receives the Millennium III Medal from IEEE in 2000.

2 Initiator and Promoter of the Information Revolution in Romania

Acad. Mihai Drăgănescu is credited with envisioning the information revolution, with its conceptual definition, and with the coordination of its development in Romania [8]. Initiator and leader of the first and only national major technologic program in the area of integrated circuits, computers and informatics, Acad. Mihai Drăgănescu has guided for 20 years, between 1965 and 1985, the economic evolution of Romania in these areas, making numerous critical decisions, including the transitioning of Romania to the silicon phase in the electronics domain, and the buying of western licenses for the manufacturing of integrated circuits and of 3rd generation computers. In 1971 he is awarded the French order "Commandeur de la Legion d'Honneur" for his contributions to the Romanian-French collaboration in Informatics.

His studies, dating back to 1970, envisioned a future information society (now a reality in the advanced countries), based on an informatics medium aimed at serving each individual, organization, and society as a whole, both in realizing its own functions and in their relationships with each other. Moreover, Acad. Mihai Drăgănescu had the vision (now confirmed by the evolution of the Internet) that such a medium had to be based on an evolving informatics system, adaptable to the evolution of computers and society. It could not be planned in the smallest details, as required by the political leaders of Romania of that time [8].

Integrating theoretical research, a global systemic vision, and a creative management, Acad. Mihai Drăgănescu has laid the basis for the development of Informatics in Romania through several outstanding initiatives. They include the establishment of important institutions, such as the Company for the

Maintenance and Repair of Computing Tools (IIRUC, 1968), the Institute of Computers (ITC, 1969), and the Institute of Electronic Components (ICE, 1969). An important moment was the establishment, in 1971, of the Central Institute for Informatics which, under his leadership, has quickly become the center of the Romanian informatics, both through world-class research in advanced domains (e.g., artificial intelligence, industrial informatics, computer networks) and through the coordination of the development of informatics in the entire country (e.g., the coordination of a network of 40 territorial computer centers, established between 1968 and 1985). At the same time computer centers have been established in universities and research institutes, as well as computer science high schools, and new university degree programs in electronics, automation, computers and informatics.

In late 70, Acad. Mihai Drăgănescu proposes a new major national program for the transitioning of Romania into the second industrial revolution, based on electronics, automation and informatics [9, 10]. Not only that the political leadership of Romania rejects this visionary proposal, but the development of informatics is purposely slowed down and, in 1985, even the Central Institute for Informatics is dismantled. "In 1985, a terrible blow was given to the information society in formation" [11]. However, even during this tragic period in his own life and that of the country, Acad. Mihai Drăgănescu formulates the idea of a future knowledge society, idea widely accepted today [12].

In the aftermath of the Romanian Revolution of 1989, Acad. Mihai Drăgănescu resumes his role of promoter of the information revolution. He establishes the National Commission for Informatics (1990), the Center for New Electronics Architectures (1991), the Section for Science and Technology of Information of the Romanian Academy (1992), the Research Institute for Artificial Intelligence (1994) and the Forum for the Information Society (1997).

Later on, Acad. Mihai Drăgănescu formulates a new vision for the evolution of the society, defining the era of information, with three stages, the Information Society, the Knowledge Society, and the Consciousness Society [12]. "In essence, the Information Society is the society based on Internet" Romania being in a state of underdevelopment of this society [12]. "For Romania the development of the Information Society is essential, but in the current situation this has to take place at the same time with achieving the first objectives of the Knowledge Society. It is wrong to say: First the Information Society and then the Knowledge Society. We should not sentence ourselves to be perpetually delayed" [12].

Acad. Mihai Drăgănescu identifies technological and functional vectors as tools that can transition the Information Society to the Knowledge Society: "To take first steps into the Knowledge Society it is necessary to employ a minimum number of such vectors. The first vector is the development of an 'advanced' Internet, which is a technological vector, then the technology of electronic books (technological vector) and the knowledge management (functional vector with two valences, one for the economic and organizational functioning of a company, multinational corporation or society, and the other one for the moral utilization of knowledge in the global society)" [12].

Similar to the national program from 1965-1985, the Program for the Information and Knowledge Society [12] is a very significant contribution of Acad. Mihai Drăgănescu, with precise objectives and means, of greatest importance for the progress of the Romanian society in the global economy.

3 Creator of the Structural-Phenomenological Philosophy of Existence (Orthophysics)

A profound understanding of physics, electronics, informatics and biology, a great analytic, synthetic and unifying spirit, an irresistible philosophical tension, in the context of the Romanian spirituality, have led Acad. Mihai Drăgănescu to the creation of an original philosophy of existence, fascinating through its naturalness and generality, a philosophy which, according to the illustrious philosopher Constantin Noica, "will deeply amaze and impress the unsuspecting thinkers of the XXI century" [13].

Acad. Mihai Drăgănescu realizes that "the ontological model which is at the basis of the structural science is inadequate, and the structural science itself is limited, it can only be used between certain limits of reality. Beyond these limits it is insufficient to explain the reality because it neglects extra ingredients of nature which in cannot recognize due to the character of the methods used. Overall, the structural science is incomplete and cannot explain the reality in its entirety" [14].

Through fundamental works, such as *The Depths of the Material World* [15], *Orthophysics* [16], *Spirituality, Information, Matter* [17], *Essays* [19], *L'Universalité ontologique de l'information* [20], Acad. Mihai Drăgănescu has developed an original ontological model which, for the first time, explains in a unified way the physical, biological, informational, mental, and psychological processes, based on original fundamental concepts such as informatter, orthoenergy, orthoexistence, orthosense, phenomenological sense, intro-openness, and others. Acad. Mihai Drăgănescu postulates the existence of a tendencial deep reality, with an energetic component (orthoenergy) and an informational one (informatter), outside space and time, from which physical universes are generated, where the non-living matter is a coupling between orthomatter with orthoenergy and informatter, while living organisms contain directly informatter, thus forming rings of existence.

The Orthophysics philosophy proposes to overcome the paradoxes of the current structural science by developing a new type of science, called structural-phenomenological, for which Acad. Mihai Drăgănescu has formulated several principles, such as the principle of insufficiency of structural knowledge, the principle of existence, of profound matter, of the ontological universality of the information and energy, of the tendencies of becoming, and of the structural-phenomenological modeling [21].

As philosopher Constantin Noica before him, Acad. Mihai Drăgănescu has made philosophy relying first and foremost on "the pure thought uninfluenced, let flowing in his mind ... feeling than the need of confrontation with the established philosophy and science, but giving science a more prominent role" [19, p.104].

Other great thinkers, such as Florian Nicolau, David Bohm and John Archibald Wheeler, have themselves imagined a more profound stratum of reality than that offered by the structural science, but none has advanced so much in this direction as Acad. Mihai Drăgănescu, who has thus made a major contribution to the human thought. Today, an increasing number of scientists in physics, chemistry, and information science adopt points of view that are close to those initially proposed by Acad. Mihai Drăgănescu, confirming the importance and the ramifications of his contributions.

A convincing argument for the generality of the orthophysics philosophy of existence is the explanation of the notion of God. The question on the relationship between the orthophysics philosophy and God was raised by Constantin Noica, in 1987. The answer is given by Acad. Mihai Drăgănescu years later, in 2003, following his interactions with Prof. Menas Kafatos, illustrious American astrophysicist and philosopher who postulated the existence of the consciousness of the universe [22].

Following a long investigation in the orthophysics philosophy, and using only the already defined principles, Acad. Mihai Drăgănescu devices a phenomenological-structural model of existence. "Which is the relationship between the phenomenological-structural model of the fundamental consciousness of existence and the notion of God from the great and important religions of the world? There is no doubt a very strong relationship, the notion of God in these religions potentially being a certain way of perceiving the fundamental consciousness of existence. If we accept the existence of the fundamental consciousness as being very plausible, then God is also very plausible from the scientific and philosophical point of view, even though He is perceived with different nuances. ... the same way the cosmos is not an organism, the fundamental consciousness does not belong to an organism, yet it exists. The fundamental consciousness of existence is the being by excellence, beyond life and, implicitly, beyond death." [23]

The fruitful collaboration with Prof. Menas Kafatos, with whom Acad. Mihai Drăgănescu has many points of view in common, has led to the development of a new integrated approach to science, which takes into account both the structural and the phenomenological aspects of reality [24, 25].

The publication of a large number of papers, the organization of several conferences on the "structural-phenomenological modeling" at the Romanian Academy, the emerging of disciples, the collaboration with reputable scientists, the adoption of similar concepts by an increasing number of thinkers, all these confirm Noica's characterization of the orthophysics philosophy [13].

4 Initiator and Manager of the Romanian Academy Renaissance

Next year the Romanian Academy will celebrate 20 years from its renaissance following the Romanian revolution of 1989. In a short period of only four years, between 1990 and 1994, as President of the re-born Romanian Academy, Acad. Mihai Drăgănescu has initiated and led the return of this primary forum of the Romanian spirituality to its traditional role and sources, as well as its renewal and adaptation to the future tendencies of the scientific and humanistic culture, in the national, European and world context.

We only need to reflect on the evolution of the Romanian society during the never-ending period of transition to understand that Acad. Mihai Drăgănescu was the right person, at the right place and at the right time. As Vice Prime Minister in the first provisional government, Acad. Mihai Drăgănescu sets the renaissance of the Romanian Academy (which was condemned at physical death by the Ceasusescu's regime) as top priority for the new government which, on January 5th, 1990, promulgates the Decree-Law no. 4 on the organization and functioning of the Romanian Academy, reestablishing its autonomy.

One of the first measures the re-born Romanian Academy under the leadership of Acad. Mihai Drăgănescu was to right the wrongs of history. Are recognized as members without interruption of the Romanian Academy the illustrious representatives of the Romanian spirituality, abusively eliminated in 1948 by the Communist regime, such as Lucian Blaga, Theodor Capidan, Dumitru Caracostea, Ion Petrovici, Constantin Rădulescu-Motru, Gheorghe I. Brătianu, Silviu Dragomir, Dimitrie Gusti, Alexandru Lepădatu, Ioan Lupaş, Simion Mehedinţi, Petre P. Negulescu, Nicolae Colan, Victor Slăvescu, Constantin Brăiloiu, Tiberiu Brediceanu, Onisifor Ghibu, Pantelimon Halipa, Dragomir Hurmuzescu, Grigore T. Popa, Petru Sergescu, Emil Haţieganu, Iuliu Hossu, Constantin Levaditi, Iuliu Maniu, Nicolae Bălan, Grigore Tăuşan, and others [19, p.153].

Shining stars who have not received their well-deserved recognition during their lives, are elected posthumously as members of the Romanian Academy: Constantin Brâncuşi, Mircea Eliade, Constantin Noica, Ştefan Lupaşcu, Mircea Florian, Nichita Stănescu, Marin Preda, Ion Barbu, Traian Lalescu, Constantin Pârvulescu, Călin Popovici, Ion Moraru, Ştefan Berceanu, Virgil Madgearu, Petre Andrei, Petru Caraman, Nicolae C. Paulescu, Alexandru Proca, Haralambie Vasiliu, Ştefan Odobleja, Bela Bartok, Herman Oberth, Eugen Lovinescu and Theodor Aman [19, p.153].

The Romanian Academy regains its historic role as forum of all Romanians through the election of honorary members from Bessarabia (Grigore Vieru, Ion Druţă, Mihai Cimpoi, Andrei Andries, Sergiu Ion Rădăuţan), Bucovina (Grigore Constantin Bostan şi Alexandrina Cernov), and the Romanian diaspora (Nicolae Georgescu-Roegen, Anghel Rugină, Radu Bălescu, Sergiu Celibidache, Alexandru Cioranescu, Joseph M. Juran, George Uscăţescu, Ion I. Inculeţ, Dinu Adameşteanu, Mihai Ion Botez, Eugenio Coşeriu, Nicola Matteesco-Matte, Jean Negulesco, Dinu C. Giurescu, Iosif Antochi, Paul Stahl, Petru Dumitriu, Mattei Dogan, Idel Ianchelevici, Constantin Atanasie Bona, and other [19, p.154], [26, p. 154-155].

Acad. Mihai Drăgănescu founds, writes its manifesto, and leads "Academica", the Romanian Academy journal destined to maintain a continuous connection with the Romanian intellectuality. Well-thinking the role of the Romanian nation in the development of the universal scientific and humanistic culture, Acad. Mihai Drăgănescu succeeds in bringing over 50 institutions of fundamental and advanced research back into the Romanian Academy, and in resurrecting institutions of tradition, successfully defending their activity against powerful opposition from various national and international forums. At the same time, Acad. Mihai Drăgănescu leads the adaptation of the Romanian Academy to the global tendencies through the founding of the Section of Arts, Architecture and Audio-Visual, the Section of Science and Technology of Information, as well as several new institutes and centers.

Another impact on the Romanian Academy by the first president of its renaissance is his initiation of the election of about 50 of its members.

5 Promoter of the Romanian Scientific and Humanistic Culture

We have already mentioned the major role played by Acad. Mihai Drăgănescu in the development of Electronics, Informatics and Philosophy. But his role as promoter of the Romanian scientific and humanistic culture is much wider than his extraordinary achievements in these areas. Consider, first of all, his determining role in the reestablishment of the natural orthography of the Romanian language, abusively altered in 1953, through political diktat contrary to the national culture. This act, of primary importance for the Romanian language, as well as the others already mentioned, shows the extraordinary humanistic and patriotic qualities of Acad. Mihai Drăgănescu. The request by the illustrious linguist, Acad. Alexandru Rosetti, of reestablishing â in the Romanian orthography, expressed just before his passing into eternity, was a "testamentary request" for Acad. Mihai Drăgănescu [26, p.206]. As a consequence, on January 31st 1991, he delivers the speech "On Several Rectifications of the Romanian Language Orthography" at the Romanian Academy [19, p.162-170]. Following a wide public debate, where he confronted the vicious opposition of several linguists and part of the press with numerous scientific arguments, Acad. Mihai Drăgănescu delivers, on February 17th, 1993, the historical speech "The Romanian Language Orthography: With Hasdeu, Maiorescu, Puşcariu and Rosetti", urging "Let us have the consciousness of our past, aspirations, and destiny. Let us defend our culture, language, and soul." [19, p.171-194]. The almost unanimous vote (with only one against) of the members of the Romanian Academy, as well as the support of the Saint Synod of the Romanian Orthodox Church, the Ministry of Education, and the Ministry of Culture, have changed the accusation of imposing "the Drăgănescu's orthography" into a title of glory [26, p. 158].

The exemplary patriotism of Acad. Mihai Drăgănescu is also shown by his relentless work toward the national and international recognition of the personalities of the Romanian culture, such as Ştefan Odobleja. Through a 15 years effort, between 1975 and 1990, during which Acad. Mihai Drăgănescu has delivered numerous talks on the contributions of Ştefan Odobleja, has led the editing of two volumes, *Romanian Precursors of Cybernetics* [27] and *Odobleja between Ampere and Wiener* [28], and has edited Odobleja's *Consonantist Psychology* in Romanian [29], he has succeeded in determining the election of Ştefan Odobleja, posthumously, as member of the Romanian Academy, and has increased the prestige of the Romanian science [19, p.153].

Through his example, Acad. Mihai Drăgănescu has also shown us how to recognize and treasure our professors and mentors. In 1982 he delivers the talk *Tudor Tănăsescu - Founder of the Romanian School of Electronics*. In 1992 he organizes the conference *Tudor Tănăsescu and the Romanian School of Electronics* at the Romanian Academy, and leads the editing of the volume *Tudor Tănăsescu - Founder of the Romanian School of Electronics* [30], solidifying his place in the history of the Romanian science and technology.

These are only a few examples from Acad. Mihai Drăgănescu's life-long sustained effort of promoting past and present values of the Romanian culture, not only through his own publications and speeches, but also through the organization of conferences and through his support for the publication of books in numerous domains.

6 Mentor and Life Model

Acad. Mihai Drăgănescu was always a visionary. He was ahead of his time when he introduced the idea of an *Information Revolution* [8], and when he created the *Orthophysics Philosophy* [15], and when he defined the concept of *Functional Electronics* [4], and when he defined the concept of *Knowledge Society* [11], and when he introduced the concept of *Consciousness Society* [14].

It is well-known that the younger generation is much better adapted to the new social context created by the computers and the Internet than the older ones. In spite of his age, Acad. Mihai Drăgănescu is part of this younger generation. In his seventies, he is the first to publish the first Romanian book on the Internet [20], as well as the first electronic book [31]. He is the one who, in 2001, organizes the first symposium in Romania on the electronic books, as well as the first symposium on the electronic commerce. How could one explain this extraordinary power of assimilation and adaptation that allowed Acad. Mihai Drăgănescu to navigate with such apparent ease the highly dynamic and complex domains of Electronics, Informatics and Philosophy?

In his reception speech at the Romanian Academy, titled "The Philosophical Tension and the Cosmic Feeling", Acad. Mihai Drăgănescu stated: "If the existence forms material world rings, or universes, then we have to accept that our universe has a sense, a tendency, and the good, in its philosophical sense, corresponds to conforming to this tendency by the human and society, which does not mean strict determinism but, to the contrary, advanced knowledge and high creation power. It can be demonstrated that the *philosophic good* is not only compatible with the social good but also theoretically derives it, as can also be shown based on humanistic considerations" [32, p.27]. The cosmic feeling, advanced by Acad. Mihai Drăgănescu as solution to the *philosophical tension* for the understanding of the existence, "calls man to a heroic attitude through thought and action in the direction of the fundamental tendency in the Universe, that is, toward creation and a spiritual attitude which is also a source for strengthening his will, rationality, and lucidity" [32, p.30]. We see here a philosophical justification of the man's action in the direction of good, which Acad. Mihai Drăgănescu exemplifies in the most remarkable manner. We think that precisely his deep understanding of the philosophical tension and the cosmic feeling explains his model patriotic vocation for the progress of the Romanian society, as well as his capacity of overcoming so many obstacles and injustices.

In a long and illustrious career, Acad. Mihai Drăgănescu has lightened and influenced the life of many generations who, as myself, have had the chance of being closer to him, well-thought by him, guided by him, and blessed by him, with unparallel generosity. *Acad. Mihai Drăgănescu is a spiritual father and life model for me*, the one who has influenced the direction of my life much more than anyone else.

7 Final Remarks

The observer of the activity of Acad. Mihai Drăgănescu is amazed by how a person can excel in domains that are so diverse and difficult. It is the genius of Acad. Mihai Drăgănescu who succeeded to discover and define a line of continuity and complementarity that has led him to the development of a unified encyclopedic work integrating the most dynamic domains of the modern society: Electronics, Informatics, and the Philosophy of Science and Society. In his words, "The multidisciplinary approach to problems has become common practice. However, this will not be sufficient if we will not find the integrative factors to melt the multidisciplinarity into a unity, be it the case of understanding a complex reality, or that of achieving goals serving the people and society" [33, p.428]. Discovering these integrative factors is one of the greatest contributions of Acad. Mihai Drăgănescu. One example: "Information technology is a technology of progress in our age, through its two important components: Electronics and Informatics. There is no boundary between them. The physical seed of the contemporary information society is Electronics, or Microelectronics to be precise, and the informational seed is provided by the Informatics" [4, p.15].

The "physical seed" and the "informational seed" may have inspired Acad. Mihai Drăgănescu in his development of the philosophical conception of deep matter: "Under the quantum world there is ... the deep matter governed by two principles: informatter, a matter with informational properties of phenomenological type (like the mental senses), and energymatter, a matter with energetic properties, which is unstructured but can be structured by the informatter" [33, p.10].

On the other hand, "Technology is inherently linked to philosophy because, as instrument of becoming, it has an existential role. However, becoming implies coalescing the social factors with the scientific, technological and economic ones, and with the spiritual-cultural life. None of these factors can be estranged from the others without affecting the reality and endangering the socio-human civilization" [18, p.127].

What ultimately provides this amazing unity in diversity to the work of Acad. Mihai Drăgănescu is his general view of information which encompasses [33, p.428]:

"I. Philosophy of Information;

II. Science of Information;

III. Technology of Information;

IV. Industry of Information;

V. Economy of Information;

VI. Culture-Information Relationship;

VII. Information Society (including the problems of social intelligence and information democracy);

VIII. Creation (Generation) of Information."

For Acad. Mihai Drăgănescu, the information "has a multitude of manifestations, it may become thought, consciousness, spirit, computation, poetry, idea, sense. Each of these manifestations may be a support for the understanding of matter and life" [18, p.13].

The encyclopedic work of Acad. Mihai Drăgănescu, spanning Electronics, Philosophy, Informatics, and Society (see http://www.racai.ro/ dragam/), is an impressive and inspiring example of a *life dedicated to the Science, Philosophy, and Romanian Society*.

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A Framework for Enhancing Competitive Intelligence Capabilities using Decision Support System based on Web Mining Techniques

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Abstract: Nowadays Competitive Intelligence (CI) represents one of the most important pieces in strategic management of organizations in order to sustain and enhance competitive advantage over competitors. There are some studies that claim that a successful strategic management is influenced by the accuracy of external environment's evaluation and, in the same time, in order to have correct and complete business strategies it is necessary to be sustained by competitive advantage. But till at the beginning of '80 the things were totally different. This paper will present the evolution and the objectives of CI, the results of using CI in organizations and how can be improved the CI process using tools and techniques provided by business intelligence (BI). The study will propose a framework of a decision support system based on web mining techniques in order to enhance capabilities of organization's competitive intelligence.
Keywords: competitive intelligence, information system, decision making process, web mining

1 Introduction

Several studies ([13], [27], [30], [28], [32]) consider that starting with the second half of the 20th century a series of researches were focused on the enhancing competitiveness of the organization based on concept of intelligence as a process. [3], [37] state that the accuracy of external environment's evaluation has a big influence over a successful strategic management and correct and complete business strategies must be sustained by competitive advantage. In the context of using methods and tools provided by information technology and communication (ITC), the increasing significance of using information and knowledge in order to obtain a competitive advantage and the enhancing ability of organization in order to maximize the efficiency of using internal and external linkages through new data and information flows [32] represent an activity which must be closely supervised in every organization.

There are studies claiming that competitive intelligence (CI), as a research area, attracted growing attention over the last two decades and especially in the last years ([7], [5]). Some of the main factors which had a great influence over this evolution are: (1) spectacular development of the information technology and communication (ITC) domain, (2) methods and tools provided by ITC, (3) exponentially use of the Internet, many CI researchers considering that Internet represents the one of the major information data sources used by CI ([36], [41], [5]).

The research objectives of this study are outlined below:

- presenting a short overview of competitive intelligence (CI) evolution and possible ways of developing in future; " identifying the objectives of using competitive intelligence (CI) in organizations;
- presenting a short overview of some specific tools and techniques provided by business intelligence (BI) which can be used in competitive intelligence;
- identifying the results of using competitive intelligence (CI) in organizations;

- proposing a framework for a decision support system using web mining techniques.

An extensive review of literature will be conducted in order to accomplish the goals of this study.

2 Definition and evolution of competitive intelligence

The literature related to intelligence suggests that are three directions for this area [5]:

- the first is represented by the military domain where can be identified one of the earliest studies regarding intelligence, which is The Art of War by Sun Tzu (translated by Griffith in 1963);
- the second is represented by the national security as a policy issue [4];
- the third is represented by the economic domain, where the intelligence determines an increasing competitiveness of organizations [12].

[21] consider that information is factual because consist in numbers, indicators, data about competitors, customers, suppliers regarding past actions of them, but intelligence represents a collection of cleaned, filtered and analyzed information that support managers in decision making process.

The modern approach of competitive intelligence (CI) was appeared after the second world war and started to become important in the ’80 [15], the indicators that are sustaining this being:

- the number of conferences having the topic competitive intelligence (CI) which is increasing constantly;
- the increasing number of books, articles, studies, papers and other types of publication about competitive intelligence (CI);
- the increasing number of academic courses and professional programs dedicated to competitive intelligence (CI);
- the developing and increasing role of Society of Competitive Intelligence Professionals (SCIP) which is a global organization with declared mission to "*be the global organization of choice for professionals engaged in competitive intelligence and related disciplines*" and to "*be the premier advocate for the skilled use of intelligence to enhance business decision-making and organizational performance*" (www.scip.org) and having the declared vision: "*Better decisions through competitive intelligence*".

Starting with the 1980 an important number of researchers tried to define the concept of competitive intelligence (CI).

CI it is represented by information which describe how competitive is an organization and, in the same time, it is being able to predict moves of the business environment actors (competitors, customers, suppliers, government etc) [16].

CI represents an iterative and systematic process for gathering and analyzing data and information about activities of competitors, business environment and business trends in order to fulfill the goals of organization [21].

CI represents a process that predicts behavior and moves of the actors (competitor, customer, suppliers, government etc) which interact with organization or influence either the business environment or the behavior of organization [6]. The results provided by CI are used in order to identify potential business opportunities and to minimize the possibility of appearance for unpredictable situations, those facts define the goal of the CI: to predict the future situations (what is going to happen) rather than debate past situations (what did happen).

CI is a process that aims to monitor the external business environment of organization in order to identify relevant information for decision making process [9].

Competitive intelligence represents a process that consists of two levels [25]:

- Accessing legal and ethical data sources (publicly or semipublicly) in order to gather data for building new data sources regarding competitors, competition, environmental conditions, past, present or future trends etc.
- Analyzing those new data sources in order to transform data into usable and valuable information and knowledge that will support the decision making process.

Summarizing all those points of view we consider that **competitive intelligence** represents a continuous process of gathering data, information and knowledge about actors (competitors, customers, suppliers, government etc) which interact with organization in the business environment in order to support decision making process for enhancing competitiveness of organization.

The CI process consists in the following steps: monitoring business environment (external data, information and knowledge), gathering, analyzing, filtering and disseminating intelligence that will support decision making process in order to increase competitiveness and improve position of organization.

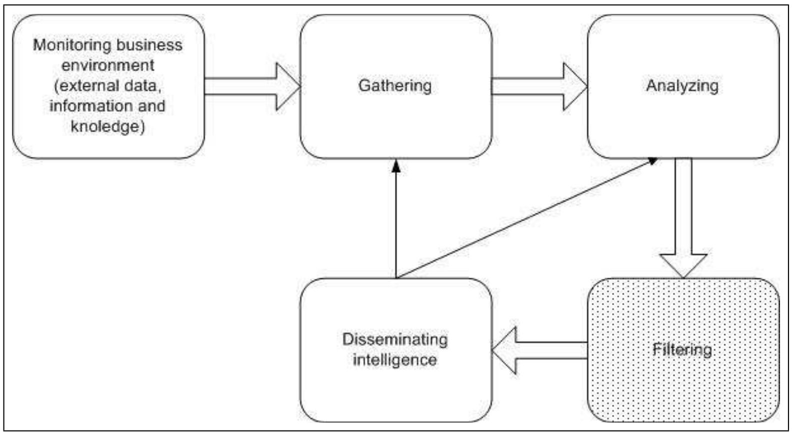

Figure 1: Competitive Intelligence (CI) process

[33] considers that evolution of CI could be divided in following stages: (1) "*Competitive Intelligence Gathering*" occurred through the 60s and 70s; (2) "*Industry and Competitor Analysis*" occurred through 1980 and 1987; (3) "*Competitive Intelligence for Strategic Decision Making*" occurred through 1987 and 2000; (4) "*Competitive Intelligence as a Core Capability*" which represent the present stage in CI evolution.

In the *Competitive Intelligence Gathering* stage of CI the key defining event was the book "*Competitive strategy*" published by Michael Porter in 1980. Personnel involved in CI activities were located mostly in Library or Marketing department and the primary skill was capability to *find* information [33]. Despite the fact that organization was collected large amount of data, over gathered data rarely were applied some static analyses. Another important thing was represented by very weak connection between CI and decision making process. Development of skills in information acquisition was the key issue of this stage.

In the *Industry and Competitor Analysis* stage of CI the key defining event was the founding of the Society of Competitive Intelligence Professionals (SCIP). Personnel involved in CI activities were located mostly in Planning or Marketing department, over gathered data were applied quantitative analyses, and between CI and decision making process was a weak connection [33]. Building a business case for CI, spy image and analytical skill development were the keys issues of this stage.

In the *Competitive Intelligence for Strategic Decision Making* stage of CI the key defining event was the establishment of the Competitive Intelligence Review. Personnel involved in CI activities were located mostly in Planning, Marketing or CI unit, over gathered data were applied quantitative and qualitative analyses, and between CI and decision making process was a strong connection. Demonstrating bottom-line input, role of information technology, CI technology, international CI, demands vs. supply-driven CI, counter-intelligence were the keys issues of this stage [33].

In the *Competitive Intelligence as a Core Capability* stage of CI the key defining event is represented by CI courses taught in universities and in business school across the world. Personnel involved in CI activities are located mostly in CI units, Planning or Marketing, over gathered data are be applied qualitative emphasis analyses and information and knowledge provided by CI represent a raw material for decision making. Managing the parallel process, intelligence infrastructures for multinationals, CI as learning, network analysis are the keys issues of this stage.

3 The objectives and results of using CI in organizations

From the beginning is important to emphasize that is not necessary that every organization to develop and implement an organized CI activity. In many cases formal information gathered from external sources (Internet, media, government etc) and informal data and information collected, analyzed and filtered by managers represent a very flexible and efficient informal CI. But in the case of some organization, an informal CI is not enough in order to support tactic and strategic decision making process, fact that conduct to develop and implement an organized CI system. The CI can be used in order to increase the capabilities of the organizational memory (OM) of the enterprise because the OM contains organizational memory information systems which are based on Knowledge Management techniques [39].

In the last years, enterprises are constantly working to improve and to enhance their operations [40]. The reasons which are staying at the base of decision to implement a CI in organization are various [21]:

- The globalization process which determine an increasing level of competition among organizations because the number of competitor is increasing and, in the same time, the quantity and quality of goods and services provided by them growing continuously.
- The new products, services, methods and tools provided by information technology and communication domain.
- The rapidly changing of the business environment where new business opportunities appear and disappear very fast and the period of time allocated for decision making processes is decreasing constantly.
- Political changes which affect and influence the business environment as well as the evolution of organizations.

A review of the literature related to objectives of using CI in organization reveals quite a wide and ambitious arrangement of objectives for CI [31].

[1] consider that objectives of using an organized information system of CI are: (1) identifying and analyzing new business opportunities or the market trends; (2) developing or updating software using latest technologies, methods and tools for software developing; (3) maximizing revenues and minimizing expenses; (4) identifying, understanding and analyzing strategies, already implemented or in the phase of implementation.

[31] consider that objectives of using an organized information system of CI are: (1) help organization in order to gain a competitive edge; (2) reveal opportunities and threats by surveying weak signals;

(3) process and combine data, information and knowledge in order to produce new knowledge about competitors, customers, suppliers etc.; (4) provide useful information for managers in decision making process and reduce the period of time used by decision making process.

In our opinion, the objectives of using an organized information system of CI in organizations are:

- Enhancing organization's competitiveness.
- Predicting, with a high level of trust, business environment's evolutions, competitors' actions, customers' requirements, even influences generated by political changes.
- Providing a better and better support for strategic decision making process.

There are studies that identify some benefit derived from using organized information system of CI [16]: (1) increasing analytical skill for managers and the ability to anticipate moves of the other actors from organization's business environment; (2) sharing ideas and knowledge inside organization in order to develop new ideas or knowledge or to integrate the existing into organization.

Some authors identified new benefits from using organized information system of CI [21]: (1) discovering new potential competitors or customers and supporting starting of new businesses (2) identifying and analyzing new technologies, products and processes that influence organization's activities and behavior; (3) identifying and analyzing political or legislative standards or regulations that influence organization's activities and behavior; (4) identifying and analyzing situations, from competitors, customers, suppliers or other, that evolved into successes or into failures.

4 Decision Support System and Web Mining

In the last years, due to the economic evolution, the amount of data and information which must be used in order to adopt better decision has increase extraordinary; therefore the decisional process from organizations has a spectacular evolution [42]. Companies gathering data from a various sources and deposit them in data warehouses which represent a collection of subject-oriented, integrated, time-variant and non-volatile data used in order to support the process of decision-making [20]. Each person involved in the process of decision-making can and must be supported in performing his activities by specialized IT tools [14]. [8] consider that Decision Support Systems (DSS) represents a specific class of information system that supports business and organizational decision-making activities.

[19] state that business intelligence represents the ability of companies of analyzing and studying the behavior and actions from previous periods of time in order to understand actual position of organization and to predict or try to change what is going to happen in future period of time. [35] consider that business intelligence is composed from following components: (1) Extraction, Transformation and Loading - ETL; (2) Data mining; (3) Online Analytical Processing - OLAP; (4) Enterprise reporting.

In last decade, the Internet growing was spectacular and the amount of information which reside on the Internet is huge and nowadays the World Wide Web became represents one of the major source of data and information for all activities [11]. In order to extract relevant information from the Web it is necessary to examine and to analyze the content, structure and usage of web resources using techniques of data mining [26]. Because the scope of data mining is the identify patterns which are hidden in large databases [29], in the last decade, the web mining technologies developed in this period determine an increasing of volume of valuable material which can easily browsed and identified over the Internet [18]. Web data mining represents a group of three concepts (Figure 2): web content mining, web structure mining and web usage mining and it is very important to make a clear distinction between these concepts ([10], [24], [22]). [34] consider that web content mining represents "*the process of searching for contextually relevant sources of web data whose embedded information can be extracted and used to generate actionable knowledge*". [24] consider that "*web structure mining tries to discover the model underlying* *the Web hyperlink structure*". [34] consider that the web usage mining represents "*the process of searching for user behavior patterns by mining the data stored in referrer logs, server access logs, and other web user behavior data repositories*".

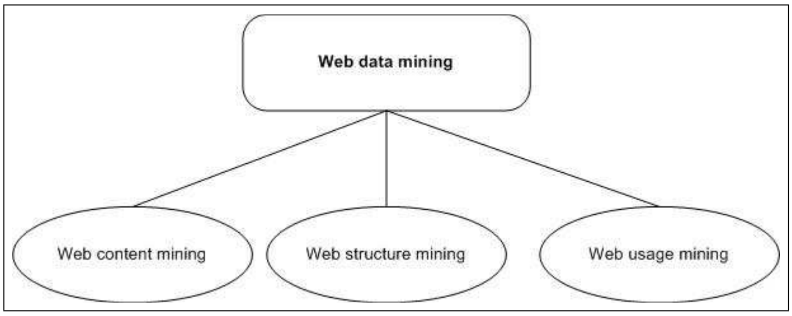

Figure 2: Structure of web data mining

There are studies ([23]; [38]) that consider that web content mining and web structure mining can be used to gather data about business competitors in order to enhance business decision-making and organizational performance

5 Proposed framework for a Decision Support System using Web mining capabilities

Because a modern company's information system must also contain data and information acquired from the web which are extremely dynamically. In the same time, during the decision making process, the information system must be updated with the latest data, information and knowledge. In this section will be presented a framework for decision support system using web mining techniques based on architecture consist of three tiers (Figure 3): decision tier, logic tier and data tier.

The decision tier, which is the top-most level of the model, receives the request from the user and invokes the logic tier for resolving the request after translating the request. After the receiving of results from logic layer, the decision layer transposes these into a format that help user to understand and use them.

The logic tier, which is the middle level of the model, has the following functions:

- gather data, information and knowledge from company's information system, invoking data mining algorithms, performing calculation, making evaluations and finally transformation of the obtained data into useful information [2];
- gather data, information and knowledge from the web using specific web mining techniques and provide them to the data tier.

Data tier store and retrieve information from all databases contained by company's information system and transmit then to the logic tier for processing.

6 Conclusions

Understanding business environment dynamics and predicting its evolution is a challenging and difficult task for every information system of CI, but represents, in the same time, one of the most expected needs and requirements from organizations. An information system of CI used in an efficient way will determine an increasing level of efficiency of adopted and applied decisions. Information system of CI

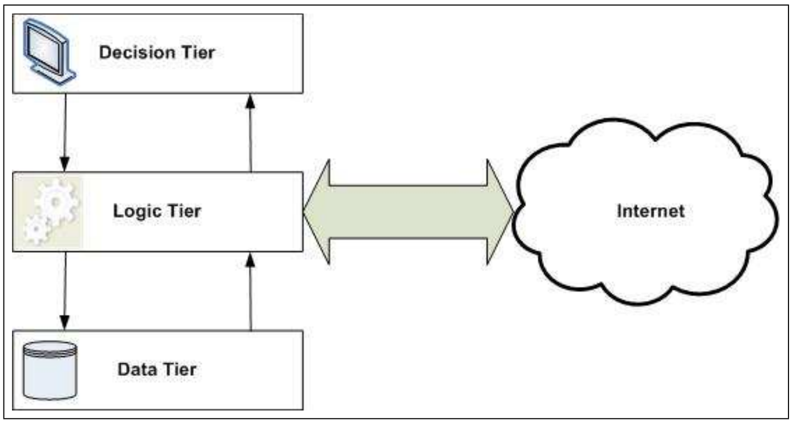

Figure 3: Framework for DSS based on web mining techniques

is recommended to be developed, implemented and used in order to create a competitive advantage over competitors and became more and more evident that CI process is necessary in every organization which intends to increase the existing level of intelligence.

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An LMI Technique for the Global Stabilization of Nonlinear Polynomial Systems

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Abstract: This paper deals with the global asymptotic stabilization of nonlinear polynomial systems within the framework of Linear Matrix Inequalities (LMIs). By employing the well-known Lyapunov stability direct method and the Kronecker product properties, we develop a technique of designing a state feedback control law which stabilizes quadratically the studied systems. Our main goal is to derive sufficient LMI stabilization conditions which resolution yields a stabilizing control law of polynomial systems.

Keywords: Nonlinear Polynomial systems, Lyapunov method, Global stabilization, Kronecker product, LMI approach.

1 Introduction

The control theoretician role may be viewed as one of developing methods that allows the control engineer to make which seems relatively natural and physically motivated [1, 2]. Generally the main and first object in the control theory is to ensure the stability and the convergence of the considered system. In this context, the problem of stabilization of nonlinear systems has received a great deal of attention and several methods have been proposed in the literature [3, 4, 5, 6]. However, the proposed approaches remain restrictive to particular classes of nonlinear models, and there is no general method for the analysis or synthesis of general nonlinear systems. That is the reason of continuing research on study and control of nonlinear systems. The polynomial systems constitute an important class of nonlinear systems which has the advantage to describe the dynamical behavior of a large set of processes as electrical machines and robot manipulators and has also the ability to approach any analytical nonlinear system, since any analytical nonlinear function can be approximated by a polynomial expansion. Let'us note that a lot of works have considered the modeling, analysis and control of the polynomial systems [7, 8, 9, 10, 11, 12, 13, 14, 15, 16]. The main key of these developments is the description of the polynomial system by using the Kronecker power of the state vector [17].

In the other hand, Linear Matrix Inequalities (LMIs) have emerged as a powerful formulation and design technique for a variety of control problems [18, 19, 20]. Since solving LMI's is a convex optimization problem, such formulation offer a numerically tractable means of attacked problems that lack an analytical solution. Besides, efficient interior-point algorithms are now available to solve the generic LMI problems. They are applied to several important process control applications including control structure selection, robust controller analysis and design, and optimal design of experiments [21, 22, 23]. Consequently, reducing a control design problem to an LMI can be considered as a practical solution [24].

The contribution of the present paper consists on the use of the Lyapunov method with a quadratic candidate function, to derive a practice sufficient condition ensuring the global asymptotic stabilization of the original equilibrium of a polynomial system. This condition is then reformulated in the form of an

LMI feasibility problem which can be solved using the numerical software as MATLAB.

This paper is organized as follows: In section 2 the description of the studied systems and necessary mathematical notations are introduced. Then, in the next section, the problem of stabilizing control law synthesis of polynomial systems is investigated. The section 4 proposes an LMI formulation of the obtained stabilization condition. An illustrative example is reported in section 5 to implement the developed approach.

2 Studied polynomial systems and Mathematical Notations

2.1 Studied polynomial systems

The studied nonlinear polynomial systems are described by the following state equation:

$$\dot{X} = f(X) + GU, \tag{1}$$

where $f(X)$ is a vectorial polynomial function of X.

$$f(X) = \sum_{i=1}^{r} F_i X^{[i]} = \sum_{i=1}^{r} \tilde{F}_i \tilde{X}^{[i]}, \tag{2}$$

with
$X = [x_1, \ldots, x_n]^T \in \mathbb{R}^n$,

$$\begin{cases} X^{[0]} = 1 \\ X^{[i]} = X^{[i-1]} \otimes X = X \otimes X^{[i-1]} \quad for \quad i \geq 1, \end{cases} \tag{3}$$

$\otimes$ is the symbol of the Kronecker product [17].

$\tilde{X}^{[i]}_{i=1,\ldots,r} \in \mathbb{R}^{n_i}$ where $n_i = \begin{pmatrix} n+i-1 \\ i \end{pmatrix}$, is the nun-redundant Kronecker power of the state vector X defined as

$$\begin{aligned} &\tilde{X}^{[1]} = X^{[1]} = X, \\ &\forall\, i \geq 2, \tilde{X}^{[i]} = [x_1^i, x_1^{i-1}x_2, \ldots, x_1^{i-1}x_n, \ldots, x_1^{i-2}x_n^2, \ldots, x_1^{i-3}x_2^3, \ldots, x_n^i]^T, \end{aligned} \tag{4}$$

i.e., the components of $\tilde{X}^{[i]}$ are the same that those of $X^{[i]}$ with omission of the repeated terms.
$F_{i,i=1,\ldots,r} \in \mathbb{R}^{n \times n^i}$ (resp. $\tilde{F}_i \in \mathbb{R}^{n \times n_i}$) are constant matrices.
The polynomial order r is considered odd: $r = 2s - 1$, with $s \in \mathbb{N}^*$.
$U \in \mathbb{R}^m$ is the input vector and G is a constant $(n \times m)$ matrix.

2.2 Notations

In this section, we introduce some useful notations and needed rules and functions. Let the matrices and vectors of the following dimensions

$$A(p \times q), B(r \times s), C(q \times f), X(n \times 1) \in \mathbb{R}^n, Y(m \times 1) \in \mathbb{R}^m.$$

(i) We consider the following notations: $I_n : (n \times n)$ identity matrix; $0_{n \times m} : (n \times m)$ zero matrix; 0: zero matrix of convenient dimension; A^T : transpose of matrix A; $A > 0 (A \geq 0)$: symmetric positive definite (semi-definite) matrix; e_k^q : q dimensional unit vector which has 1 in the k^{th} element and zero elsewhere.

(ii) The relation between the redundant and the nun-redundant Kronecker power of the state vector X can be stated as follows

$$\begin{cases} \forall i \in \mathbb{N} \ \exists \ ! \quad T_i & \in & \mathbb{R}^{n^i \times n_i}, \\ X^{[i]} & = & T_i \tilde{X}^{[i]}, \end{cases} \tag{5}$$

A procedure of the determination of the matrix T_i is given in [25].

(iii) The permutation matrix denoted $U_{n\times m}$ is defined as

$$U_{n\times m} = \sum_{i=1}^{n}\sum_{k=1}^{m} \left(e_i^n \cdot (e_k^m)^T\right) \otimes \left(e_k^m \cdot (e_i^n)^T\right). \tag{6}$$

This matrix is square $(nm \times nm)$ and has precisely a single 1 in each row and in each column. Among the main properties of this matrix presented in [17], [11], we recall the following useful ones

$$(B \otimes A) = U_{r\times p}(A \otimes B)U_{q\times s}, \tag{7}$$

$$(X \otimes Y) = U_{n\times m}(Y \otimes X), \tag{8}$$

$$\forall i \leq k \quad X^{[k]} = U_{n^i \times n^{k-i}} X^{[k]}. \tag{9}$$

(iv) An important vector valued function of matrix denoted $vec(.)$ was defined in [17] as follows

$$A = \left[\begin{array}{cccc} c_1 & c_2 & \dots & c_q \end{array}\right] \in \mathbb{R}^{p\times q},$$

where

$$\forall i \in \{1,...,q\},\ c_i \in \mathbb{R}^p \text{ are the columns of A}$$

$$vec(A) = \left[\begin{array}{cccc} c_1^T & c_2^T & \dots & c_q^T \end{array}\right]^T \in \mathbb{R}^{pq}.$$

We recall the following useful rules [17] of this function

$$vec(BAC) = (C^T \otimes B)vec(A), \tag{10}$$

$$vec(A^T) = U_{p\times q} vec(A). \tag{11}$$

(v) A special function $mat_{(n,m)}(.)$ can be defined as follows
if V is a vector of dimension $p = n.m$ then $M = mat_{(n,m)}(V)$ is the $(n \times m)$ matrix verifying $V = vec(M)$.

(vi) For a polynomial vectorial function

$$a(X) = \sum_{i=1}^{r} A_i X^{[i]}, \tag{12}$$

where $X \in \mathbb{R}^n$ and A_i are $(n \times n^i)$ constant matrices, we define the $(\upsilon \times \upsilon)$ matrix $\mathcal{M}(a)$ as

$$\mathcal{M}(a) = \begin{bmatrix} M_{11}(A_1) & M_{12}(A_2) & 0 & \dots & 0 \\ 0 & M_{22}(A_3) & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & 0 \\ \vdots & & \ddots & M_{s-1,s-1}(A_{2s-3}) & M_{s-1,s}(A_{2s-2}) \\ 0 & \dots & \dots & 0 & M_{s,s}(A_{2s-1}) \end{bmatrix}, \tag{13}$$

with $\upsilon = n + n^2 + ... + n^s$.

- For $j = 1, ..., s$

$$M_{j,j}(A_{2j-1}) = \begin{bmatrix} mat_{(n^{j-1},n^j)}\left(A_{2j-1}^{1T}\right) \\ mat_{(n^{j-1},n^j)}\left(A_{2j-1}^{2T}\right) \\ \vdots \\ mat_{(n^{j-1},n^j)}\left(A_{2j-1}^{nT}\right) \end{bmatrix}, \tag{14}$$

- For $j = 1, ..., s-1$

$$M_{j,j+1}(A_{2j}) = \begin{bmatrix} mat_{(n^{j-1},n^j)}\left(A_{2j}^{1T}\right) \\ mat_{(n^{j-1},n^j)}\left(A_{2j}^{2T}\right) \\ \vdots \\ mat_{(n^{j-1},n^j)}\left(A_{2j}^{nT}\right) \end{bmatrix}, \tag{15}$$

where A_k^i is the i^{th} row of the matrix A_k

$$A_k = \left[\begin{array}{cccc} A_k^{1T} & A_k^{2T} & ... & A_k^{nT} \end{array}\right]^T. \tag{16}$$

(vii) We introduce the matrix $\mathcal{R}$ defined by

$$\mathcal{R} = \tau_1^{+[2]} \cdot \mathcal{U} \cdot \mathcal{H} \cdot \tau_2, \tag{17}$$

where

$$\tau_1 = Diag\left(T_{i,i=1,...,s}\right), \tag{18}$$

with τ_1^+ is the Moore-Penrose pseudo-inverse of τ_1 and $\tau_1^{+^{[2]}} = \tau_1^+ \otimes \tau_1^+$.

$$\tau_2 = Diag\left(T_{j,j=2,...,2s}\right), \tag{19}$$

$$\mathcal{U} = Diag\left(U_{n^{i,i=1,...,s} \times \eta_0}\right), \tag{20}$$

$$\mathcal{H} = \begin{bmatrix} I_{\eta_1} & & & & 0 \\ 0_{\eta_2 \times \eta_1} & I_{\eta_2} & & & \\ 0_{\eta_3 \times (\eta_1+\eta_2)} & & I_{\eta_3} & & \\ \vdots & & & \ddots & \\ 0_{\eta_s \times (\eta_1+\eta_2+...+\eta_{s-1})} & & & & I_{\eta_s} \end{bmatrix}, \tag{21}$$

for $j = 0, ..., s : \eta_j = n^j \cdot \left(\sum_{i=1}^{s} n^i\right)$.
We note Γ the matrix defined by

$$\Gamma = \left(I_{\eta^2} + U_{\eta \times \eta}\right)\left(\mathcal{R}^{+T}\mathcal{R}^T - I_{\eta^2}\right), \tag{22}$$

with $\eta = \sum_{j=1}^{s} n_j = \sum_{j=1}^{s} \left(\begin{array}{c} n+j-1 \\ j \end{array} \right)$ and $\mathcal{R}^+$ is the Moore-Penrose pseudo-inverse of $\mathcal{R}$.

$$\beta = rank(\Gamma) \tag{23}$$

and $C_{i,\, i=1,\ldots,\beta}$ are β linearly independent columns of Γ.

(iix) For a $(n \times l)$ matrix ϕ, we define $\mathcal{D}_s(\phi)$ the $(\upsilon \times \upsilon)$ matrix defined as

$$\mathcal{D}_s(\phi) = \begin{bmatrix} \phi & & & 0 \\ & \phi \otimes I_n & & \\ & & \ddots & \\ 0 & & & \phi \otimes I_{n^{s-1}} \end{bmatrix}. \tag{24}$$

In the case where the matrix ϕ is square $(l = n)$, the matrix $\mathcal{D}_s(\phi)$ is also square $(\upsilon \times \upsilon)$, with υ is defined in (vi). As well, if ϕ is square and is symmetric positive definite, then so is $\mathcal{D}_s(\phi)$.

3 The Proposed Global Stabilization Condition of Controlled Polynomial Systems

We consider the polynomial nonlinear systems defined by the equation (1). Our purpose is to determine a polynomial feedback control law

$$U = k(X) = \sum_{i=1}^{r} K_i X^{[i]}, \tag{25}$$

with $K_{i,i=1,\ldots,r}$ are constant gains matrices which stabilizes asymptotically and globally the equilibrium $(X = 0)$ of the considered system.
Applying this control law to the open-loop system (1), one obtains the closed-loop system

$$\begin{aligned} \dot{X} &= a(X) = (f + Gk)(X), \\ &= \sum_{i=1}^{r} A_i X^{[i]}, \end{aligned} \tag{26}$$

where

$$A_i = F_i + GK_i. \tag{27}$$

Using a quadratic Lyapunov function $V(X)$ and computing the derivative $\dot{V}(X)$, lead to the sufficient condition of the global asymptotic stabilization of the polynomial system, given by the following theorem 1.

Theorem 1. *The nonlinear polynomial system defined by the equation (1) is globally stabilized by the control law (25), if there exist*

- *an $(n \times n)$-symmetric positive definite matrix P;*
- *arbitrary parameters $\mu_{i,i=1,\ldots,\beta} \in \mathbb{R}$;*
- *gain matrices $K_{i,i=1,\ldots,r}$;*

such that the $(\eta \times \eta)$ *symmetric matrix* $\mathcal{Q}$ *defined by*

$$\begin{aligned} \mathcal{Q} &= \tau_1^T[\mathcal{D}_S(P)\mathcal{M}(f)+\mathcal{M}(f)^T\mathcal{D}_S(P)]\tau_1+\tau_1^T[\mathcal{D}_S(P)\mathcal{G}\mathcal{M}(k)+(\mathcal{D}_S(P)\mathcal{G}\mathcal{M}(k))^T]\tau_1 \\ &+ \sum_{i=1}^{\beta}\mu_i mat_{(\eta,\eta)}(C_i), \end{aligned} \tag{28}$$

be negative definite.
Where β *and* $C_{i,i=1,\ldots,\beta}$ *are defined in (23).*

Proof. Consider the quadratic Lyapunov function

$$V(X) = X^T P X, \tag{29}$$

Differentiating $V(X)$ along the trajectory of the system (26), we obtains

$$\begin{aligned} \dot{V}(X) &= \sum_{k=1}^{r}(X^T PA_k X^{[k]} + X^{[k]^T}A_k^T PX), \\ &= 2\sum_{k=1}^{r} X^T PA_k X^{[k]}. \end{aligned} \tag{30}$$

Using the rule of the vec-function (10), the relation (30) can be written as

$$\dot{V}(X) = 2\sum_{k=1}^{r} V_k^T X^{[k+1]}, \tag{31}$$

where

$$V_k = vec(PA_k). \tag{32}$$

We can write

$$\sum_{k=1}^{r=2s-1} V_k^T X^{[k+1]} = \sum_{j=1}^{s-1} V_{2j}^T X^{[2j+1]} + \sum_{j=1}^{s} V_{2j-1}^T X^{[2j]}, \tag{33}$$

using the mat-function defined in section 2, one has

$$\dot{V}(X) = 2[\sum_{j=1}^{s-1} X^{[j]^T} mat_{(n^j,n^{j+1})}(V_{2j}^T)X^{[j+1]} + \sum_{j=1}^{s} X^{[j]^T} mat_{(n^j,n^j)}(V_{2j-1}^T)X^{[j]}]. \tag{34}$$

Applying the following lemma [11]

Lemma 2. *Consider a* $(n \times n^k)$ *matrix* A $(k \in \mathbb{N})$ *and a* $(n \times n)$ *matrix* P.
Let i *and* j *two integers verifying* $i + j = k + 1$ *and* $i \geq 1$. *Then*

$$mat_{(n^i,n^j)}(vec(PA)) = U_{n^{i-1}\times n}(P \otimes I_{n^{i-1}}).\mathbb{M},$$

with

$$\mathbb{M} = \begin{bmatrix} mat_{(n^{i-1},n^j)}\left(A^{1T}\right) \\ mat_{(n^{i-1},n^j)}\left(A^{2T}\right) \\ \vdots \\ mat_{(n^{i-1},n^j)}\left(A^{nT}\right) \end{bmatrix},$$

where A^i *denotes the* i^{th} *row of the matrix* A

$$A = \begin{bmatrix} A^{1T} & A^{2T} & \ldots & A^{nT} \end{bmatrix}^T$$

leads to the following relations

$$mat_{(n^j,n^{j+1})}(V_{2j}^T) = U_{n^{j-1}\times n}(P \otimes I_{n^{j-1}})M_{j,j+1}(A_{2j}), \tag{35}$$

$$mat_{(n^j,n^j)}(V_{2j-1}^T) = U_{n^{j-1}\times n}(P \otimes I_{n^{j-1}})M_{j,j}(A_{2j-1}), \tag{36}$$

where $M_{j,j+1}(A_{2j})$ and $M_{j,j}(A_{2j-1})$ are defined respectively in (15) and (14) and $U_{n^{j-1}\times n}$ is mentioned in (20).
Using the results (35) and (36), the equality (34) can be expressed as

$$\begin{array}{rcl} \dot{V}(X) & = & 2[\sum_{j=1}^{s-1} X^{[j]^T} U_{n^{j-1}\times n}(P \otimes I_{n^{j-1}})M_{j,j+1}(A_{2j})X^{[j+1]} \\ & + & \sum_{j=1}^{s} X^{[j]^T} U_{n^{j-1}\times n}(P \otimes I_{n^{j-1}})M_{j,j}(A_{2j-1})X^{[j]}], \end{array} \tag{37}$$

by means of the relation (9), one obtains

$$\dot{V}(X) = 2[\sum_{j=1}^{s-1} X^{[j]^T}(P \otimes I_{n^{j-1}})M_{j,j+1}(A_{2j})X^{[j+1]} + \sum_{j=1}^{s} X^{[j]^T}(P \otimes I_{n^{j-1}})M_{j,j}(A_{2j-1})X^{[j]}]. \tag{38}$$

Consequently, we obtain

$$\begin{array}{rcl} \dot{V}(X) & = & 2\mathcal{X}^T \mathcal{D}_S(P)\mathcal{M}(a)\mathcal{X}, \\ & = & \mathcal{X}^T(\mathcal{D}_S(P)\mathcal{M}(a) + \mathcal{M}(a)^T \mathcal{D}_S(P))\mathcal{X}, \end{array} \tag{39}$$

with

$$\mathcal{X} = \begin{bmatrix} X^T & X^{[2]^T} & \cdots & X^{[s]^T} \end{bmatrix}^T \tag{40}$$

$\mathcal{D}_S(P)$ and $\mathcal{M}(a)$ are defined respectively in (24) and (13).
Using the nun-redundant Kronecker product power form, the vector $\mathcal{X}$ can be written as

$$\mathcal{X} = \tau_1 \tilde{\mathcal{X}}, \tag{41}$$

where $\widetilde{\mathcal{X}} = \begin{bmatrix} \widetilde{X}^T & \widetilde{X}^{[2]^T} & \cdots & \widetilde{X}^{[s]^T} \end{bmatrix}^T \in \mathbb{R}^{\eta}$, $\eta = \sum_{j=1}^{s} n_j$ and τ_1 is defined in (18).
Then $\dot{V}(X)$ can be written in the following form

$$\dot{V}(X) = \widetilde{\mathcal{X}}^T \tau_1^T(\mathcal{D}_S(P)\mathcal{M}(a) + \mathcal{M}(a)^T \mathcal{D}_S(P))\tau_1 \widetilde{\mathcal{X}}, \tag{42}$$

A sufficient condition of the global asymptotic stability of the equilibrium $(X = 0)$ is that the quadratic form $\dot{V}(X)$ is negative definite. This condition can be ensured if there exists a symmetric negative definite $\mathcal{Q} \in \mathbb{R}^{\eta\times\eta}$ such that

$$\widetilde{\mathcal{X}}^T \tau_1^T(\mathcal{D}_S(P)\mathcal{M}(a) + \mathcal{M}(a)^T \mathcal{D}_S(P))\tau_1 \widetilde{\mathcal{X}} = \widetilde{\mathcal{X}}^T \mathcal{Q} \widetilde{\mathcal{X}}, \tag{43}$$

using the *vec*-function, the equality (43) can be expressed as

$$vec^T\left(\mathcal{Q} - \tau_1^T(\mathcal{D}_S(P)\mathcal{M}(a) + \mathcal{M}(a)^T \mathcal{D}_S(P))\tau_1\right)\widetilde{\mathcal{X}}^{[2]} = 0. \tag{44}$$

But, it can be easily checked that $\widetilde{\mathcal{X}}^{[2]}$ can be written as

$$\widetilde{\mathcal{X}}^{[2]} = \mathcal{R}\widetilde{\mathcal{X}}_2, \tag{45}$$

where

$$\widetilde{\mathcal{X}}_2 = \left[\begin{array}{cccccc} \widetilde{\mathcal{X}}^{[2]T} & \dots & \widetilde{\mathcal{X}}^{[s+1]T} & \widetilde{\mathcal{X}}^{[s+2]T} & \dots & \widetilde{\mathcal{X}}^{[2s]T} \end{array}\right]^T, \tag{46}$$

and $\mathcal{R}$ is the matrix defined in (17). The proof of the relation (45) is given in [11].
Therefore the equality (44) yields the following equation

$$\mathcal{R}^T vec(S) = 0, \tag{47}$$

with: $S = \mathcal{Q} - \tau_1^T \left(\mathcal{D}_S(P)\mathcal{M}(a) + \mathcal{M}(a)^T \mathcal{D}_S(P)\right)\tau_1$.
The η^2-vector $vec(S)$ solution of (47) can be expressed as

$$vec(S) = \left(\mathcal{R}^{+T}\mathcal{R}^T - I_{\eta^2}\right)\mathcal{Y}, \tag{48}$$

where $\mathcal{Y}$ is an arbitrary vector of $\mathbb{R}^{\eta^2}$.
The matrix S is symmetric since $\mathcal{Q}$ is symmetric, then we can write

$$S = \tfrac{1}{2}(S + S^T), \tag{49}$$

and using the property (11) yields

$$vec(S) = \tfrac{1}{2}(I_{\eta^2} + U_{\eta\times\eta})vec(S) = \sum_{i=1}^{\beta} \mu_i C_i, \tag{50}$$

where
• $\beta = rank\left[(I_{\eta^2} + U_{\eta\times\eta})\left(\mathcal{R}^{+T}\mathcal{R}^T - I_{\eta^2}\right)\right]$,
• $C_{i,i=1,\dots,\beta}$ are β linearly independent columns of

$$(I_{\eta^2} + U_{\eta\times\eta})\left(\mathcal{R}^{+T}\mathcal{R}^T - I_{\eta^2}\right), \tag{51}$$

• $\mu_{i,i=1,\dots,\beta}$ are arbitrary values.
Consequently, the symmetric matrix $\mathcal{Q}$ verifying (47) is of the following form

$$\mathcal{Q} = \tau_1^T(\mathcal{D}_S(P)\mathcal{M}(a) + \mathcal{M}(a)^T\mathcal{D}_S(P))\tau_1 + \sum_{i=1}^{\beta}\mu_i mat_{(\eta,\eta)}(C_i). \tag{52}$$

According to (26) and the following lemma [10]

Lemma 3. *Let $G \in \mathbb{R}^{n\times m}$, $k(.)$ a polynomial vectorial function defined in (25) and $G.k(.)$ the resultant product of G by $k(.)$, then one has*

$$\mathcal{M}(G.k) = \mathcal{G}\mathcal{M}(k),$$

where $\mathcal{G} = D_s(G)$ and $\mathcal{M}(.)$ the matrix function defined in (13).

Thus, we can write

$$\mathcal{M}(a) = \mathcal{M}(f + Gk) = \mathcal{M}(f) + \mathcal{G}\mathcal{M}(k), \tag{53}$$

finally, we obtain the following quadratic form of the symmetric matrix $\mathcal{Q}$

$$\begin{aligned} \mathcal{Q} &= \tau_1^T[\mathcal{D}_S(P)\mathcal{M}(f) + \mathcal{M}(f)^T\mathcal{D}_S(P)]\tau_1 + \tau_1^T[\mathcal{D}_S(P)\mathcal{G}\mathcal{M}(k) + \mathcal{M}(k)^T\mathcal{G}^T\mathcal{D}_S(P)]\tau_1 \\ &+ \sum_{i=1}^{\beta}\mu_i mat_{(\eta,\eta)}(C_i). \end{aligned} \tag{54}$$

If $\mathcal{Q}$ is negative definite, then the derivative $\dot{V}(X)$ is negative definite.
Which ends the proof. □

4 Stabilizing Control Synthesis using the LMI approach

In this section we show how the stabilization problem stated by the theorem 1 can be formulated as an LMI feasibility problem.
Let recall that our main problem is to find

- gain matrices $K_{i,i=1,\ldots,r}$;
- a $(n \times n)$ matrix P;
- real parameters $\mu_{i,i=1,\ldots,\beta}$;

such that

$$P > 0, \tag{55}$$

$$\begin{aligned}&\tau_1^T[\mathcal{D}_S(P)\mathcal{M}(f) + \mathcal{M}(f)^T\mathcal{D}_S(P)]\tau_1 + \tau_1^T[\mathcal{D}_S(P)\mathcal{G}\mathcal{M}(k) + \mathcal{M}(k)^T\mathcal{G}^T\mathcal{D}_S(P)]\tau_1\\ &+ \sum_{i=1}^{\beta}\mu_i mat_{(\eta,\eta)}(C_i) < 0.\end{aligned} \tag{56}$$

Note that this problem is nonlinear with respect of the unknown parameters P,K_i and μ_i, since the inequality (56) is bilinear on (P, K_i). To overcome this problem we make use of the known Schur's complement [18] and we exploit the separation lemma [26]. In this sequel we transform the BMI problem into LMI problem as it is shown in the following development.
Making use of the following separation lemma [26]

Lemma 4. *For any matrices A and B with appropriate dimensions and for any positive scalar $\varepsilon > 0$, one has:*

$$A^TB + B^TA \leq \varepsilon A^TA + \varepsilon^{-1}B^TB,$$

one obtains

$$\begin{aligned}\mathcal{Q} \leq\ & \tau_1^T[\mathcal{D}_S(P)\mathcal{M}(f) + \mathcal{M}(f)^T\mathcal{D}_S(P)]\tau_1 + \sum_{i=1}^{\beta}\mu_i mat_{(\eta,\eta)}(C_i)\\ &+ \gamma\tau_1^T\mathcal{D}_S(P)^T\mathcal{D}_S(P)\tau_1 + \gamma^{-1}\tau_1^T\mathcal{M}(k)^T\mathcal{G}^T\mathcal{G}\mathcal{M}(k)\tau_1,\end{aligned} \tag{57}$$

with $\gamma > 0$.
Then, to ensure that the matrix $\mathcal{Q}$ is negative definite, it is sufficient to have

$$\begin{aligned}&\tau_1^T[\mathcal{D}_S(P)\mathcal{M}(f) + \mathcal{M}(f)^T\mathcal{D}_S(P)]\tau_1 + \sum_{i=1}^{\beta}\mu_i mat_{(\eta,\eta)}(C_i)\\ &- \tau_1^T\mathcal{D}_S(P)^T(-\gamma I)\mathcal{D}_S(P)\tau_1 - \tau_1^T\mathcal{M}(k)^T\mathcal{G}^T(-\gamma^{-1}I)\mathcal{G}\mathcal{M}(k)\tau_1 < 0.\end{aligned} \tag{58}$$

Using the Generalized Schur's complement, the inequality (58) is equivalent to

$$\begin{bmatrix} \tau_1^T(\mathcal{D}_S(P)\mathcal{M}(f) + \mathcal{M}(f)^T\mathcal{D}_S(P))\tau_1 + \sum_{i=1}^{\beta}\mu_i mat_{(\eta,\eta)}(C_i) & (\mathcal{D}_S(P)\tau_1)^T & (\mathcal{G}\mathcal{M}(k)\tau_1)^T \\ \mathcal{D}_S(P)\tau_1 & -\gamma^{-1}I & 0 \\ \mathcal{G}\mathcal{M}(k)\tau_1 & 0 & -\gamma I \end{bmatrix} < 0, \tag{59}$$

when pre-and post-multiplying the inequality (59) by $\Xi = diag(I, I, \gamma^{-1}I)$, we get

$$\begin{bmatrix} \tau_1^T(\mathcal{D}_S(P)\mathcal{M}(f) + \mathcal{M}(f)^T\mathcal{D}_S(P))\tau_1 + \sum_{i=1}^{\beta}\mu_i mat_{(\eta,\eta)}(C_i) & (\mathcal{D}_S(P)\tau_1)^T & (\mathcal{G}\mathcal{W}(k)\tau_1)^T \\ \mathcal{D}_S(P)\tau_1 & -\gamma^{-1}I & 0 \\ \mathcal{G}\mathcal{W}(k)\tau_1 & 0 & -\gamma^{-1}I \end{bmatrix} < 0, \tag{60}$$

with $\mathcal{W}(k) = \gamma^{-1}\mathcal{M}(k)$.
This new inequality is linear on the decision variables, and then we can state the following result.

Theorem 5. *The equilibrium $(X = 0)$ of the system (1) is globally asymptotically stabilizable if there exist*

- *a $(n \times n)$-symmetric positive definite matrix P ;*
- *arbitrary parameters $\mu_{i,i=1,\dots,\beta} \in \mathbb{R}$;*
- *gain matrices $K_{i,i=1,\dots,r}$;*
- *a real $\gamma > 0$;*

such that

$$P > 0, \tag{61}$$

and

$$\begin{bmatrix} \tau_1^T(\mathcal{D}_S(P)\mathcal{M}(f) + \mathcal{M}(f)^T\mathcal{D}_S(P))\tau_1 + \sum_{i=1}^{\beta}\mu_i mat_{(\eta,\eta)}(C_i) & (\mathcal{D}_S(P)\tau_1)^T & (\mathcal{G}\mathcal{W}(k)\tau_1)^T \\ \mathcal{D}_S(P)\tau_1 & -\gamma^{-1}I & 0 \\ \mathcal{G}\mathcal{W}(k)\tau_1 & 0 & -\gamma^{-1}I \end{bmatrix} < 0. \tag{62}$$

Thus, a stabilizing control law (25) for the considered polynomial system (1) can be characterized by applying the following procedure

1. Solve the LMI feasibility problem i.e., find the matrices $\mathcal{D}_S(P)$, $\mathcal{W}(k)$ and the parameters μ_i and γ such that the inequalities (61), (62) are verified.
2. Extract the gain matrices K_i from the relation $\mathcal{M}(k) = \gamma\mathcal{W}(k)$.

This optimization problem can be carried out using MATLAB software. To provide the effectiveness of the proposed approach, we consider the following numerical example.

5 Illustrative Example

Our aim in this section is to apply the proposed approach for the global stabilization of the following polynomial system

$$\begin{cases} \dot{x}_1 &= -x_1 + x_2 + x_1^2 + x_1x_2 - x_1^3 + x_1^2x_2 - x_1x_2^2 + 2x_2^3, \\ \dot{x}_2 &= -x_1 + 1.5x_2 - x_1^2 - 0.5x_1x_2 - x_1^3 - x_1^2x_2 + 0.5x_1x_2^2 - 2x_2^3 + u. \end{cases} \tag{63}$$

Using the Kronecker product, this system can be described by the following compact state equation

$$\dot{X} = F_1X + F_2X^{[2]} + F_3X^{[3]} + GU, \tag{64}$$

with

$$F_1 = \begin{bmatrix} -1 & 1 \\ -1 & 1.5 \end{bmatrix} \quad F_2 = \begin{bmatrix} 1 & 1 & 0 & 0 \\ -1 & -0.5 & 0 & 0 \end{bmatrix} \quad F_3 = \begin{bmatrix} -1 & 1 & 0 & -1 & 0 & 0 & 0 & 2 \\ -1 & -1 & 0 & 0.5 & 0 & 0 & 0 & -2 \end{bmatrix}$$

and $G = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$.

We are interested with the stabilization of the origin equilibrium $(X = 0)$ of the system (64).

Let us note that the uncontrolled $(U = 0)$ non linear system is unstable since the matrix F_1 has an unstable eigenvalue.

Solving the optimization problem formulated by theorem 2, we obtain

$$\begin{cases} \mu_1 = -0.0319 \\ \mu_2 = 0.0246 \\ \mu_3 = 0.1928 \end{cases} \quad ; \quad P = \begin{bmatrix} 0.0246 & 0.0063 \\ 0.0063 & 0.0071 \end{bmatrix} \quad ; \quad \gamma = 2.0240.$$

The searched gain matrices, extracted from $\mathcal{M}(k)$, are given by

$$K_1 = \begin{bmatrix} -9.8872 & -5.5518 \end{bmatrix} \quad K_2 = \begin{bmatrix} 2.1050 & 0.8966 & 0 & 0 \end{bmatrix}$$
$$K_3 = \begin{bmatrix} -0.8541 & -4.2706 & -1.3702 & -8.8084 & 0.9371 & -1.8216 & 4.3152 & 1.3277 \end{bmatrix}$$

Then a global stabilizing control law can be characterized for the studied system using the previous developed method. This control law can be expressed as

$$U = K_1 X + K_2 X^{[2]} + K_3 X^{[3]}. \tag{65}$$

The Figure 1 shows the behavior of the state variables $x_1(t)$ and $x_2(t)$ of the controlled system from initial conditions which were taken sufficiently far from the initial conditions $(x_1(0) = -10, x_2(0) = 10)$. It appears that the state variables converge into the origin point which confirm the asymptotic stability of the controlled system.

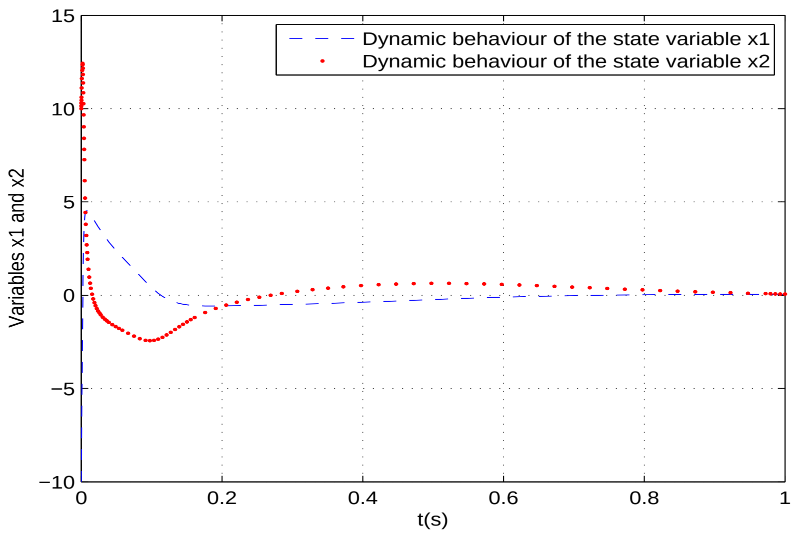

Figure 1: Closed-loop responses of the system (64) with the control law (65).

6 Conclusion

In this paper, an original technique has been proposed for the global and asymptotic stabilization of the nonlinear polynomial systems. This new stabilizing approach is based on the Lyapunov direct method and elaborated algebraic developments using the Kronecker product properties. This development has allowed the formulation of the system stabilization condition as an LMI feasibility problem, which resolution leads to a polynomial control law ensuring the quadratic stability in the whole state space of the considered system. Further works, will consider extension of these results to the robust stabilization of polynomial uncertain systems.

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Generalized Modus Ponens using Fodor's Implication and T-norm Product with Threshold

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Abstract: Using Generalized Modus Ponens reasoning, we examine the values of the inferred conclusion depending on the correspondence between the premise of the rule and the observed fact. The conclusion is obtained using Fodor's implication in order to represent a fuzzy if-then rule with a single input single output and the t-norm with threshold generated by t-norm product, as a compositional operator. A comparison study with the case when the standard t-norm product is used is made. Some comments and an example are presented in order to show how the obtained results can be used.
Keywords: t-norm, t-conorm, negation, implication, fuzzy number, generalized modus ponens rule

1 Introduction

The database of a rule-based system may contain imprecisions which appear in the description of the rules given by the expert. The imprecision implies the difficulty of representing the rules expressed, generally, by means of natural language. Another difficulty is the utilization of these rules in approximate reasoning when the observed facts do not match the condition of the rule. In order to obtain an imprecise conclusion from imprecise premises, Zadeh extends the traditional Modus Ponens rule obtaining Generalized Modus Ponens (GMP). An investigation of GMP inference was made by many papers: [2], [3], [4], [5], [7], [9], [14], [15], [27], [28], [29], [30], [33], [34], [35]. Also, we analyzed this type of inference in some papers: [19] , [22], [24] , [25], [26].
The proposition

$$X\ is\ A$$

can be understood as

$$the\ quantity\ X\ satisfies\ the\ predicate\ A$$

or

$$the\ variable\ X\ takes\ its\ values\ in\ the\ set\ A.$$

The semantic content of the proposition

$$X\ is\ A$$

can be represented by

$$\pi_X = \mu_A,$$

where π_X is the possibility distribution restricting the possible value of X and μ_A is the membership function of the set A.

Because the majority of practical applications work with trapezoidal or triangular distributions and these representations are still a subject of various recent papers ([1], [13] and [16], for instance) we will work with membership functions represented by trapezoidal fuzzy numbers. Such a number $N = (a,b,\alpha,\beta)$ is defined as

$$\mu_N(x) = \begin{cases} 0 \;\; for \;\; x < a-\alpha \\ \dfrac{x-a+\alpha}{\alpha} \;\; for \;\; x \in [a-\alpha, a] \\ 1 \;\; for \;\; x \in [a,b] \\ \dfrac{b+\beta-x}{\beta} \;\; for \;\; x \in [b, b+\beta] \\ 0 \;\; for \;\; x > b+\beta \end{cases}$$

Let X and Y be two variables whose domains are U and V, respectively. A causal link from X to Y is represented as a conditional possibility distribution [35, 36] $\pi_{Y/X}$ which restricts the possible values of Y for a given value of X. For the rule

$$if\ X\ is\ A\ then\ Y\ is\ B$$

we have

$$\forall\ u\ \in U,\ \forall\ v\ \in V,\ \pi_{Y/X}(v,u) = \mu_A(u) \to \mu_B(v)$$

where $\to$ is an implication operator and μ_A and μ_B are the possibility distributions of the propositions "$X\ is\ A$" and "$Y\ is\ B$", respectively.
If $\mu_{A'}$ is the possibility distribution of the proposition

$$X\ is\ A'$$

then from the rule

$$if\ X\ is\ A\ then\ Y\ is\ B$$

and the fact

$$X\ is\ A'$$

Generalized Modus Ponens rule computes the possibility distribution $\mu_{B'}$ of the conclusion

$$Y\ is\ B'$$

as

$$\mu_{B'}(v) = \sup_{u \in U} T\left(\mu_{A'}(u), \pi_{Y/X}(v,u)\right),$$

where T is a t-norm.

2 Basic concepts

The main concepts used in GMP are presented below, using the terminology of [8], [17] and [32].

Definition 1. A function $T : [0,1]^2 \to [0,1]$ is a t-norm iff it is commutative, associative, non-decreasing and $T(x,1) = x\ \forall x \in [0,1]$.

Definition 2. A function $S : [0,1]^2 \to [0,1]$ is a t-conorm iff it is commutative, associative, non-decreasing and $S(x,0) = x\ \forall x \in [0,1]$.

Definition 3. A function $N : [0,1] \to [0,1]$ is a strong negation iff it is an involutive and continuous decreasing function from $[0,1]$ to itself.

In order to represent a rule, the notion of fuzzy implication is used. We recall an axiomatic approach (formulated by Fodor in [10, 11, 12]) to the definition of fuzzy implication.

Definition 4. An implication is a function $I : [0,1]^2 \to [0,1]$ satisfying the following conditions:

I1: If $x \leq z$ then $I(x,y) \geq I(z,y)$ for all $x,y,z \in [0,1]$

I2: If $y \leq z$ then $I(x,y) \leq I(x,z)$ for all $x,y,z \in [0,1]$

I3: $I(0,y) = 1$ (falsity implies anything) for all $y \in [0,1]$

I4: $I(x,1) = 1$ (anything implies tautology) for all $x \in [0,1]$

I5: $I(1,0) = 0$ (Booleanity)

The following properties could be important in some applications:

I6: $I(1,x) = x$ (tautology cannot justify anything) for all $x \in [0,1]$

I7: $I(x,I(y,z)) = I(y,I(x,z))$ (exchange principle) for all $x,y,z \in [0,1]$

I8: $x \leq y$ if and only if $I(x,y) = 1$ (implication defines ordering) for all $x,y \in [0,1]$

I9: $I(x,0) = N(x)$ for all $x \in [0,1]$ is a strong negation

I10: $I(x,y) \geq y$ for all $x,y \in [0,1]$

I11: $I(x,x) = 1$ (identity principle) for all $x \in [0,1]$

I12: $I(x,y) = I(N(y),N(x))$ for all $x,y \in [0,1]$ and a strong negation N

I13: I is a continuous function.

The most important families of implications are given by

Definition 5. A S-implication associated with a t-conorm S and a strong negation N is defined by

$$I_{\mathtt{S}}^{S,N}(x,y) = S(N(x),y)\ \forall x,y \in [0,1]$$

A R-implication associated with a t-norm T is defined by

$$I_{\mathtt{R}}^{T}(x,y) = \sup\{z \in [0,1] | T(x,z) \leq y\}\ \forall x,y \in [0,1]$$

A QL-implication is defined by

$$I_{\mathtt{QL}}^{T,S,N}(x,y) = S(N(x),T(x,y))\ \forall x,y \in [0,1]$$

One of the most important implications is the Fodor's implication

$$I_F(x,y) = \begin{cases} 1 & if\ \ x \leq y \\ max(1-x,y) & otherwise \end{cases}$$

which is [5] a R-implication for $T = min_0$, a S -implication for $S = max_0$ and a QL-implication for $T = min$ and $S = max_0$, where

$$min_0(x,y) = \begin{cases} 0 & if\ \ x+y \leq 1 \\ min(x,y) & if\ \ x+y > 1 \end{cases}$$

and

$$max_0(x,y) = \begin{cases} 1 & if\ \ x+y \geq 1 \\ max(x,y) & if\ \ x+y < 1 \end{cases}$$

and $N(x) = 1 - x$. Besides, the Fodor's implication verifies the properties I1-I12. An important class of t-norms (t-conorms) is given by the t-norms (t-conorms) with thresholds, obtained from standard t-norms (t-conorms); the number of thresholds is an integer $n \geq 1$. First example of operators with 1-threshold were given by Pacholczyk in [31]. Various families of such t-operators can be found in [18, 20, 21, 23], where the advantage of their usage to represent the uncertain knowledge is justified. In this paper we analyze the results obtained by reasoning with imprecise knowledge using a t-norm with threshold as a composition operator. Finally we will compare these results with those obtained using the corresponding standard operators. We consider the following t-norm with a single threshold $k \in (0,1)$[31]

$$T_k(x,y) = \begin{cases} \frac{k}{1-k} T\left(\frac{1-k}{k}x, \frac{1-k}{k}y\right) & if \ \ x \leq k \ \ and \ \ y \leq k \\ min(x,y) & if \ \ x > k \ \ or \ \ y > k \end{cases}$$

obtained from the t-norm $T(x,y)$. We will work with the t-norm generated by $T_P(x,y) = xy$, which is one of the most used; it results

$$T_k(x,y) = \begin{cases} \frac{1-k}{k}xy & if \ \ x \leq k \ \ and \ \ y \leq k \\ min(x,y) & if \ \ x > k \ \ or \ \ y > k \end{cases}$$

3 Main results

Taking into account the following reasons, we shall work with rules having a single input single output:

a) a rule with multiple consequent can be treated as a set of rules with a single conclusion; for instance, the rule

$$if \ antecedent \ then \ C_1 \ and \ C_2 \ and \ .... \ and \ C_n$$

is equivalent to the rules

$$if \ antecedent \ then \ C_1$$

$$if \ antecedent \ then \ C_2$$

....

$$if \ antecedent \ then \ C_n.$$

b) a rule with multiple premise can be broken up into simple rules [6] when the rules are represented with any S-implication or any R-implication and the observations are normalized fuzzy sets.
Our aim is to obtain the conclusion "$Y \ is \ B'$" from the rule

$$if \ X \ is \ A \ then \ Y \ is \ B$$

and the fact

$$X \ is \ A'$$

where the fuzzy sets A, A', B and B' are represented by trapezoidal possibility distributions. The set B' is computed as

$$\mu_{B'}(v) = \sup_{u \in U} T_k(\mu_{A'}(u), I_F(\mu_A(u), \mu_B(v))),$$

analyzing five cases, depending on the relation between μ_A and $\mu_{A'}$.

Theorem 6. *If the premise contains the observation, i. e.* $\mu_{A'}(u) \leq \mu_A(u)\ \forall u \in U$, *then*

$$\mu_{B'}(v) = \mu_B(v)\ if\ \mu_B(v) \geq 0.5$$

$$\mu_{B'}(v) \in [\mu_B(v), 1-\mu_B(v))\ if\ \mu_B(v) < 0.5$$

Proof. i1) value on the set $U_1 = \{u \in U / \mu_A(u) \leq \mu_B(v)\}$
Because $I_F(\mu_A(u), \mu_B(v)) = 1$, we have

$$\mu_{B'}(v) = \sup_{u \in U_1} T_k(\mu_{A'}(u), 1) = \sup_{u \in U_1} \mu_{A'}(u) \leq \mu_B(v).$$

i2) value on the set
$U_2 = \{u \in U / \mu_A(u) > \mu_B(v) \geq 0.5\} \cup \{u \in U / \mu_A(u) > 1 - \mu_B(v) > 0.5\}$
We have $I_F(\mu_A(u), \mu_B(v)) = \mu_B(v)$. If $k < \mu_B(v)$ then

$$\mu_{B'}(v) = \sup_{u \in U_2} T_k(\mu_{A'}(u), \mu_B(v)) = \sup_{u \in U_2} min(\mu_{A'}(u), \mu_B(v)) = \mu_B(v).$$

For $k \geq \mu_B(v)$ and $U_2^1 = \{u \in U_2 / \mu_{A'}(u) \leq k\}$ we have

$$\mu_{B'}(v) = \sup_{u \in U_2^1} T_k(\mu_{A'}(u), \mu_B(v)) = \sup_{u \in U_2^1} \frac{1-k}{k} \mu_{A'}(u) \mu_B(v) \leq (1-k)\mu_B(v) < \mu_B(v).$$

For $k \geq \mu_B(v)$ and $U_2^2 = \{u \in U_2 / \mu_{A'}(u) > k\}$ we obtain

$$\mu_{B'}(v) = \sup_{u \in U_2^2} T_k(\mu_{A'}(u), \mu_B(v)) = \sup_{u \in U_2^2} min(\mu_{A'}(u), \mu_B(v)) = \mu_B(v).$$

i3) value on the set $U_3 = \{u \in U / \mu_B(v) < \mu_A(u) \leq 1 - \mu_B(v)\}$
In this case $I_F(\mu_A(u), \mu_B(v)) = 1 - \mu_A(u)$ and therefore

$$\mu_{B'}(v) = \sup_{u \in U_3} T_k(\mu_{A'}(u), 1 - \mu_A(u)).$$

For $k < \mu_B(v)$ we have $1 - \mu_A(u) \geq \mu_B(v) > k$ and $T_k \equiv min$. It results

$$\mu_{B'}(v) = \sup_{u \in U_3} min(\mu_{A'}(u), 1 - \mu_A(u)) < 1 - \mu_B(v).$$

For $\mu_B(v) \leq k \leq 1 - \mu_B(v)$ we analyze the cases:
$i3_1$): value on the set $U_3^1 = \{u \in U / \mu_B(v) \leq \mu_A(u) < 1 - k\}$
Because $k < 1 - \mu_A(u)$ we obtain

$$\begin{aligned} \mu_{B'}(v) &= \sup\nolimits_{u \in U_3^1} T_k(\mu_{A'}(u), 1 - \mu_A(u)) \\ &= \sup\nolimits_{u \in U_3^1} min(\mu_{A'}(u), 1 - \mu_A(u)) < min(1-k, 1-\mu_B(v)) = 1-k. \end{aligned}$$

$i3_2$): value on the set $U_3^2 = \{u \in U / \mu_B(v) < 1 - k \leq \mu_A(u) \leq 1 - \mu_B(v)\}$
In this case, $1 - \mu_A(u) \leq k$ and we study three possibilities, depending on $\mu_{A'}(u)$.
$i3_2^1$): on the set $U_3^{2,1} = \{u \in U_3^2 / \mu_{A'}(u) = 0\}$ we obtain $\mu_{B'}(v) = 0$
$i3_2^2$): on the set $U_3^{2,2} = \{u \in U_3^2 / \mu_{A'}(u) \in (0, k]\}$ we have

$$\mu_{B'}(v) = \sup_{u \in U_3^{2,2}} \frac{1-k}{k} \mu_{A'}(u)(1 - \mu_A(u)) < k(1-k).$$

$i3_2^3$): on the set $U_3^{2,3} = \{u \in U_3^2 / \mu_{A'}(u) > k\}$ we get

$$\mu_{B'}(v) = \sup_{u \in U_3^{2,3}} min(\mu_{A'}(u), 1 - \mu_A(u)) < 1 - \mu_B(v).$$

For $k > 1 - \mu_B(v)$ we consider the set

$$U_3^3 = \{u \in U_3 / \mu_B(v) > 1 - k\} = \{u \in U / 1 - k < \mu_B(v) < \mu_A(u) \leq 1 - \mu_B(v)\}$$

and we work with the subsets of U_3^3 for which $\mu_{A'}(u) = 0$, $\mu_{A'}(u) \in (0, k]$ and $\mu_{A'}(u) > k$, respectively; we obtain the following corresponding results:

$$\mu_{B'}(v) = 0,\ \mu_{B'}(v) < k(1-k)\ and\ \mu_{B'}(v) < 1 - \mu_B(v).$$

Synthesizing the previous results, one obtain the conclusion formulated in the theorem. □

Theorem 7. *If the premise and the observation coincide, i. e.* $\mu_A(u) = \mu_{A'}(u)\ \forall u \in U$, *then*

$$\mu_{B'}(v) = \mu_B(v)\ if\ k > 0.5\ and\ \mu_B(v) \geq 1 - k,$$

$$\mu_{B'}(v) \in [\mu_B(v), 1 - k)\ if\ k > 0.5\ and\ \mu_B(v) < 1 - k,$$

$$\mu_{B'}(v) = max(0.5, \mu_B(v))\ if\ k \leq 0.5.$$

Proof. In this case one repeat the proof of the Theorem 6 taking account the equality $\mu_A(u) = \mu_{A'}(u)$ $\forall u \in U$. It results:

1) if $0.5 < k \leq \mu_B(v)$ then $\mu_{B'}(v) = \mu_B(v)$
2) if $k \leq 0.5 \leq \mu_B(v)$ then $\mu_{B'}(v) = \mu_B(v)$
3) if $k \leq \mu_B(v) < 0.5$ then $\mu_{B'}(v) = 0.5$
4) if $\mu_B(v) \leq k \leq 0.5$ then $\mu_{B'}(v) = 0.5$
5) if $0.5 \leq \mu_B(v) < k$ then $\mu_{B'}(v) = \mu_B(v)$
6) if $\mu_B(v) \leq 0.5 < k$ then $\mu_{B'}(v) = \mu_B(v)\ if\ \mu_B(v) \geq 1 - k$ and

$$\mu_{B'}(v) \in [\mu_B(v), 1 - k)\ if\ \mu_B(v) < 1 - k$$

from which we get the conclusion. □

Theorem 8. *If the observation contains the premise, i. e.* $\mu_A(u) \leq \mu_{A'}(u)\ \forall u \in U$, *then*

$$\mu_{B'}(v) \geq max(\mu_B(v), \frac{1-k}{k}\mu_B(v)(1 - \mu_B(v)))\ if\ \mu_B(v) \leq min(0.5, k)$$

$$\mu_{B'}(v) \geq \mu_B(v)\ otherwise.$$

Proof. i1) value on the set $U_1 = \{u \in U / \mu_A(u) \leq \mu_B(v)\}$
Because $I_F(\mu_A(u), \mu_B(v)) = 1$ we have

$$\mu_{B'}(v) = \sup_{u \in U_1} min(\mu_{A'}(u), 1) = \sup_{u \in U_1} \mu_{A'}(u) \geq \mu_B(v).$$

i2) value on the set $U_2 = \{u \in U / 0.5 \leq \mu_B(v) < \mu_A(u)\} \cup \{u \in U / \mu_A(u) > 1 - \mu_B(v) > 0.5\}$
In this case $I_F(\mu_A(u), \mu_B(v)) = \mu_B(v)$ and

$i2_1$) for $k < \mu_B(v)$ we obtain

$$\mu_{B'}(v) = \sup_{u \in U_2} T_k(\mu_{A'}(u), \mu_B(v)) = \sup_{u \in U_2} min(\mu_{A'}(u), \mu_B(v)) = \mu_B(v)$$

$i2_2$) for $k \geq \mu_B(v)$ we consider two subsets of U_2:

$i2_2^1$) on the subset $U_2^1 = \{u \in U_2 / \mu_{A'}(u) \le k\}$ we have

$$\mu_{B'}(v) = \sup_{u \in U_2^1} T_k(\mu_{A'}(u), \mu_B(v)) = \sup_{u \in U_2^1} \frac{1-k}{k} \mu_{A'}(u)\mu_B(v)) \le (1-k)\mu_B(v) < \mu_B(v)$$

$i2_2^2$) on the subset $U_2^2 = \{u \in U_2 / \mu_{A'}(u) > k\}$ we have

$$\mu_{B'}(v) = \sup_{u \in U_2^2} T_k(\mu_{A'}(u), \mu_B(v)) = \sup_{u \in U_2} min(\mu_{A'}(u), \mu_B(v)) = \mu_B(v).$$

i3) value on the set $U_3 = \{u \in U / \mu_B(v) < \mu_A(u) \le 1 - \mu_B(v)\}$.
In this case $I_F(\mu_A(u), \mu_B(v)) = 1 - \mu_A(u)$ and we analyze the following cases.

i) if $k < \mu_B(v)$ then

$$\mu_{B'}(v) = \sup_{u \in U_3} T_k(\mu_{A'}(u), 1 - \mu_A(u)) = min(\mu_{A'}(u), 1 - \mu_A(u)) < 1 - \mu_B(v).$$

ii) if $k \ge \mu_B(v)$ we consider the following subcases:

ii_1) $\mu_B(v) \le k \le 1 - \mu_B(v)$

ii_1^1) on the set $U_3^1 = \{u \in U_3 / \mu_B(v) \le \mu_A(u) < 1 - k\}$ we have

$$\mu_{B'}(v) = \sup_{u \in U_3^1} min(\mu_{A'}(u), 1 - \mu_A(u)) < 1 - \mu_B(v)$$

ii_1^2) on the set $U_3^2 = \{u \in U_3 / 1 - k \le \mu_A(u) \le 1 - \mu_B(v)\}$ we consider two subsets:

• $U_3^{2,1} = \{u \in U_3^2 / \mu_{A'}(u) \le k\}$ for which we obtain

$$\mu_{B'}(v) = \sup_{u \in U_3^{2,1}} \frac{1-k}{k} \mu_{A'}(u)(1 - \mu_A(u)) \ge \sup_{u \in U_3^{2,1}} \frac{1-k}{k} \mu_A(u)(1 - \mu_A(u))$$

$$\ge max((1-k)^2, \frac{1-k}{k} \mu_B(v)(1 - \mu_B(v))) \ge \frac{1-k}{k} \mu_B(v)(1 - \mu_B(v))$$

• $U_3^{2,2} = \{u \in U_3^2 / \mu_{A'}(u) > k\}$ for which we have

$$\mu_{B'}(v) = \sup_{u \in U_3^{2,2}} min(\mu_{A'}(u), 1 - \mu_A(u)) < 1 - \mu_B(v).$$

ii_2) $k > 1 - \mu_B(v)$ which defines the set

$$U_3^3 = \{u \in U_3 / 1 - k < \mu_B(v)\} = \{u \in U / 1 - k < \mu_B(v) < \mu_A(u) \le 1 - \mu_B(v)\}$$

• for $\mu_{A'}(u) \le k$ we obtain

$$\mu_{B'}(v) = \sup_{u \in U_3^3} \frac{1-k}{k} \mu_{A'}(u)(1 - \mu_A(u))$$

$$\ge \sup_{u \in U_3^3} \frac{1-k}{k} \mu_A(u)(1 - \mu_A(u)) \ge \frac{1-k}{k} \mu_B(v)(1 - \mu_B(v))$$

• for $\mu_{A'}(u) > k$ it results

$$\mu_{B'}(v) = \sup_{u \in U_3^3} min(\mu_{A'}(u), 1 - \mu_A(u)) < 1 - \mu_B(v).$$

Finally we obtain the conclusion formulated in the theorem. □

Theorem 9. *If there is a partial overlapping between the sets A and A' then*

$$\mu_{B'}(v) = 1 \ if \ core(A') \cap (U - A_{\mu_B(v)}) \ne \emptyset \ and$$
$$\mu_{B'}(v) \ge \mu_B(v) \ otherwise$$

where A_α denotes the α-cut of A.

Proof. i1) The case $core(A') \cap (U - A_{\mu_B(v)}) \neq \emptyset$.
On the set $U_1 = \{u \in U / \mu_A(u) \leq \mu_B(v)\}$ we have $I_F(\mu_A(u), \mu_B(v)) = 1$ and therefore

$$\mu_{B'}(v) = \sup_{u \in U_1} T_k(\mu_{A'}(u), 1) = 1.$$

i2) The case $core(A') \cap (U - A_{\mu_B(v)}) = \emptyset$.
On the set $U_2 = \{u \in U / \mu_A(u) > \mu_B(v) \geq 0.5\}$ we have $I_F(\mu_A(u), \mu_B(v)) = \mu_B(v)$ and therefore

$$\mu_{B'}(v) = \sup_{u \in U_2} T_k(\mu_{A'}(u), \mu_B(v)) \geq T_k(1, \mu_B(v)) = \mu_B(v).$$

If $\mu_B(v) < 0.5$ we analyze three cases. Let $\tilde{U} = \{u \in U / \mu_A(u) = \mu_B(v)\}$; $card(\tilde{U}) = 2$ if $0 < \mu_B(v) < 1$.
$i2_1$) the case $\tilde{U} \cap supp(A') = \emptyset$ and $core(A') \cap core(A) \neq \emptyset$.
On the set $U_3 = \{u \in U / \mu_A(u) \geq 1 - \mu_B(v) > 0.5\}$ it results

$$\mu_{B'}(v) = \sup_{u \in U_3} T_k(\mu_{A'}(u), \mu_B(v)) \geq T_k(1, \mu_B(v)) = \mu_B(v).$$

$i2_2$) the case $\tilde{U} \cap supp(A') = \emptyset$ and $core(A') \cap core(A) = \emptyset$.
We consider the set $U_4 = \{u \in U / \mu_B(v) < \mu_A(u) \leq 1 - \mu_B(v)\}$; on the set $U_5 = U_3 \cup U_4$ we have

$$\mu_{B'}(v) = \sup_{u \in U_5} T_k(\mu_{A'}(u), I_F(\mu_A(u), \mu_B(v))) \geq \sup_{u \in U_5} T_k(\mu_{A'}(u), \mu_B(v)) \geq T_k(1, \mu_B(v)) = \mu_B(v).$$

$i2_3$) the case $\tilde{U} \cap supp(A') \neq \emptyset$. On the set U_5 we obtain $\mu_{B'}(v) \geq \mu_B(v)$, as in the previous case.
It results that, in the case i2), $\mu_{B'}(v) \geq \mu_B(v)$. The same result is obtained for $\mu_B(v) \in \{0, 1\}$. □

We consider the negation with threshold $k \in (0, 1)$ [31]

$$N_k(x) = \begin{cases} 1 - \frac{1-k}{k}x & if \ \ x \leq k \\ \frac{k}{1-k}(1-x) & if \ \ x \geq k \end{cases}$$

obtained from the standard negation $N(x) = 1 - x$.

Theorem 10. *If the premise and the observation are contradictory, i.e.* $\mu_{A'}(u) = N_k(\mu_A(u)) \ \forall u \in U$, *then* $\mu_{B'}(v) = 1 \ \forall v \in V$.

Proof. On the set $U_1 = \{u \in U / \mu_A(u) \leq \mu_B(v)\}$ we have

$$\mu_{B'}(v) = \sup_{u \in U_1} T_k(\mu_{A'}(u), 1) = \sup_{u \in U_1} min(\mu_{A'}(u), 1) = \sup_{u \in U_1} \mu_{A'}(u) = \sup_{u \in U_1} N_k(\mu_A(u)) = 1$$

because there is $u_0 \in U_1$ with $\mu_A(u_0) = 0$. □

4 Interpretation and utilization of results

In this section we will compare the results given by the common operators (t-norm product $T_P(x,y) = xy$ and negation $N(x) = 1 - x$) with those obtained by the corresponding operators with threshold and we will indicate some possibility of their utilization in a fuzzy reasoning system. An example of working with these results is also presented. In the case of standard operators T_P and N, according to [24] we have:

Theorem 11. *If the premise contains the observation, i.e $\mu_{A'}(u) \leq \mu_A(u) \quad \forall u \in U$, then*

$$\mu_{B'}(v) = \mu_B(v) \; if \; \mu_B(v) \geq 0.5 \; or \; (0.25 \leq \mu_B(v) < 0.5)$$

$$\mu_{B'}(v) < 0.25 \; if \; \mu_B(v) < 0.25$$

Theorem 12. *If the premise and the observation coincide, i.e. $\mu_A(u) = \mu_{A'}(u) \; \forall u \in U$, then*

$$\mu_{B'}(v) = \max(\mu_B(v), 0.25)$$

Theorem 13. *If the observation contains the premise, i.e. $\mu_A(u) \leq \mu_{A'}(u) \; \forall u \in U$, then*

$$\mu_{B'}(v) \geq \mu_B(v) \; \forall v \in V.$$

Theorem 14. *If there is a partial overlapping between the sets A and A', then*

$$\mu_{B'}(v) = 1 \; if \; core(A') \cap (U - A_{\mu_B(v)}) \neq \emptyset \; and$$

$$\mu_{B'}(v) \geq \mu_B(v) \; otherwise$$

where A_α denotes the $\alpha-$cut of A.

Theorem 15. *If the premise and the observation are contradictory, i.e. $\forall u \in U \; \mu_{A'}(u) = 1 - \mu_A(u)$, then $\mu_{B'}(v) = 1 \; \forall v \in V$.*

If the observation is more precise than the premise of the rule then it gives more information than the premise. However, it does not seem reasonable to think that the Generalized Modus Ponens allows to obtain a conclusion more precise than that of the rule. The result of the inference is valid if $\mu_{B'}(v) = \mu_B(v)$, $\forall v \in V$. Sometimes, the deduction operation allows the reinforcement of the conclusion, as is specified in [28], [19] and [25]:

Rule: *If the tomato is red then the tomato is ripe.*

Observation: *This tomato is very red.*

If we know that the maturity degree increases with respect to color, we can infer "*this tomato is very ripe*". On the other hand, in the example

Rule: *If the melon is ripe then it is sweet*

Observation: *The melon is very ripe*

we do not infer that "*the melon is very sweet*" because it can be so ripe that it can be rotten.

This examples show that if the expert has not supplementary information about the connection between the variation of the premise and the conclusion, he must be satisfied with the conclusion $\mu_{B'}(v) = \mu_B(v)$. The Theorem 6 gives a valid result if we choose $\mu_{B'}(v) = \mu_B(v)$ for $\mu_B(v) < 0.5$. As opposite, the corresponding Theorem 11 from the case of the standard t-norm T_P does not allow to obtain a valid result if $\mu_B(v) < 0.25$.

When the observation and the premise of the rule coincide the convenient behavior of the fuzzy deduction is to obtain an identical conclusion. A different conclusion indicates the appearance of an uncertainty in the conclusion. The both theorems, 7 and 12, give an uncertain conclusion, but we can choose $k > 0.75$ in the Theorem 7 and we obtain a better result, because the uncertainty is smaller in comparison with the result from the Theorem 12.

If the observation contains the premise, because

$$max(\frac{1-k}{k}\mu_B(v)(1-\mu_B(v)), \mu_B(v)) \geq \mu_B(v)$$

it results that Theorem 8 gives a better result that Theorem 13. In this case the inferred conclusion B' is a superset of B; we can choose the first superset.

If there is a partial overlapping between the premise and the observation or the premise and the observation are contradictory then the two t-norms give the same results for the inferred conclusion. The value $\mu_{B'}(v) = 1$ obtained in these cases represents an indeterminate conclusion, all elements $v \in V$ having a possibility equal to 1. In the case of "partial overlapping" we propose a "mediation" between the two possible values:

$$\mu_{B'}(v) = 1 \; and \; \mu_{B'}(v) \geq \mu_B(v);$$

if B_1, B_2, ..., B_k are the supersets of B with

$$\mu_{B_k}(v) \geq \mu_{B_{k-1}}(v) \geq .... \geq \mu_{B_1}(v),$$

we can choose $B' = B_{[\frac{k}{2}]}$, where $[x]$ is the greatest integer which is smaller than or equal to x. The Theorem 10 gives a waited result, that represents one of the basic properties of GMP reasoning.

The results from Theorems 6-10 can be used in a fuzzy inference system as in the following example. A customer is interested to buy a computer. The quality of the computer depends on its price as is specified by the rules:

Rule1: If the price is very low then the quality is below average
Rule2: If the price is very very high then the quality is very good.
Rule3: If the price is middle then the quality is good.

The variable price has values in the following set of linguistic terms

$$L_p = \{very\ very\ low, very\ low, low, midle, high, very\ high, very\ very\ high\}$$

and the variable quality has values in the set

$$L_q = \{poor, below\ average, average, above\ average, good, very\ good\}.$$

We consider the universes of discourse $[0, 2200]$ for price and $[0, 10]$ for quality. The linguistic terms are represented by the following trapezoidal fuzzy numbers:

$very\ very\ low = (0, 100, 0, 100)$
$very\ low = (0, 200, 0, 200)$
$low = (400, 700, 100, 100)$
$middle = (900, 1300, 300, 300)$
$high = (1500, 1700, 200, 200)$
$very\ high = (2000, 2200, 200, 0)$
$very\ very\ high = (2100, 2200, 100, 0)$
$poor = (1, 9, 1, 1)$
$below\ average = (3, 7, 2, 2)$
$average = (3.5, 6.5, 1.5, 1.5)$
$above\ average = (4, 6, 1, 1)$
$good = (4.5, 5.5, 0.5, 0.5)$
$very\ good = (4.75, 5.25, 0.5, 0.5)$.

These fuzzy numbers are depicted in the Figures 1 and 2.

We consider the observations:

Observation1: the price is very very low
Observation2: the price is very high
Observation3: the price is high

The theorems 6-10, used together with the comments from this section, give the following results:

1) the conclusion obtained from Rule1 and Observation1 is "the quality is below average"; this result is obtained with Theorem 6

2) Theorem 8 is applied for Rule2 and Observation2 and gives the conclusion "the quality is good"

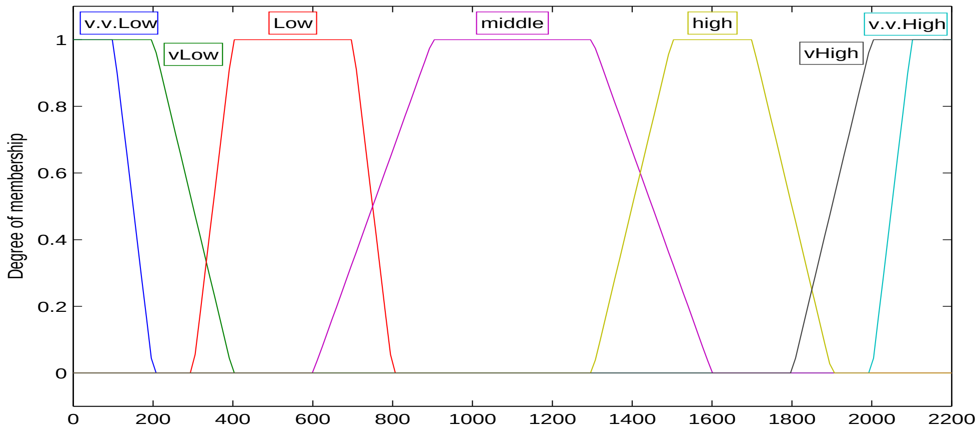

Figure 1: Fuzzy sets for linguistic terms from the list L_p

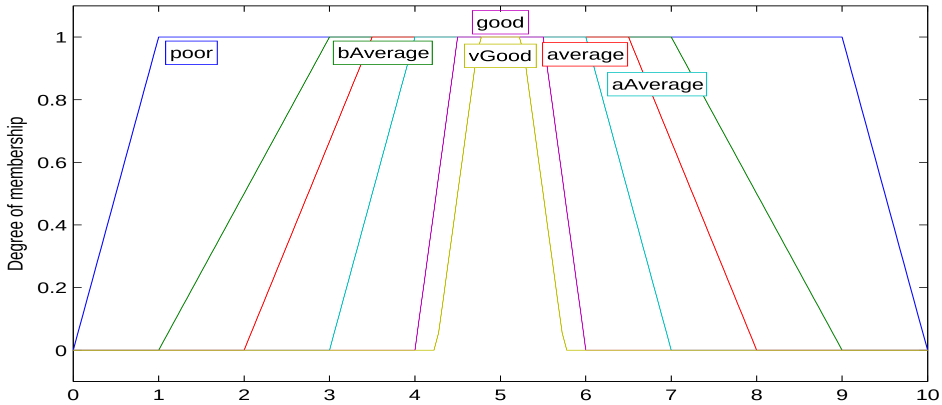

Figure 2: Fuzzy sets for linguistic terms from the list L_q

3) using Theorem 9 for the Rule3 and Observation3 one obtain the conclusion "the quality is average".

As it can be observed from this example, our results allow us to obtain the inferred conclusion by a very simple calculus in comparison with the standard formula used in GMP.

5 Summary and Conclusions

The results obtained in this paper explain how the Generalized Modus Ponens rule works with the Fodor's implication and the t-norm product with threshold. Combining these results with the approximations proposed in the previous section we obtain a fast answer for the value of the conclusion inferred by GMP reasoning. We worked with the t-norm product because it is one of the most used in practical applications. As it results from the previous sections, one obtain better results in the case of t-norm with threshold. In a future paper we will analyze the results given by another t-norms with threshold and another implications.

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Fuzzy Logic in Genetic Regulatory Network Models

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Abstract: Interactions between genes and the proteins they synthesize shape genetic regulatory networks (GRN). Several models have been proposed to describe these interactions, been the most commonly used those based on ordinary differential equations (ODEs). Some approximations using piecewise linear differential equations (PLDEs), have been proposed to simplify the model non linearities. However they not allways give good results. In this context, it has been developed a model capable of representing small GRN, combining characteristics from the ODE's models and fuzzy inference systems (FIS). The FIS is trained through an artificial neural network, which forms an Adaptive Nertwork-based Fuzzy Inference System (ANFIS). This network allows to adapt the membership and output functions from the FIS according to the training data, thus, reducing the previous knowledge needed to model the specific phenomenon.

In addition, Fuzzy Logic allows to express their rules through linguistic labels, which also allows to incorporate expert knowledge in a friendly way. The proposed model has been used to describe the Lac Operon in E. Coli and it has been compared with the models already mentioned. The outcome errors due to the training process of the ANFIS network are comparable with those of the models based on ODEs. Additionally, the fuzzy logic approach provides modeling flexibility and knowledge acquisition advantages.

Keywords: Genetic Regulatory Network, Fuzzy Logic, ANFIS, Differential Equations, Lac Operon

1 Introduction

Factors in charge of regulating the expression of a gene can be both environmental (such as produced by other factors genes) or those produced by other genes or even the same gene under regulation. The latter is the basis for understanding the so-called Genetic Regulatory Networks (GRN), since they are real networks of interaction between genes in a cell. Being able to accurately predict these interactions using mathematical and / or computational models would benefit a wide variety of applications such as medicine or agriculture.

There have been many approaches to model these networks, such as Bayesian Networks, Boolean Networks, models based on Ordinary Differential Equations, Piecewise Linear Models, Stochastic Models and others [13], [14], [13], [17]. From them, we can to highlight the models based on Ordinary Differential Equations (ODEs) since they describe biological phenomena in large detail, being used primarily for modeling small regulatory networks. A disadvantage of these models is the large number of parameters (to be known a priori) acceptable for a biological description, requiring an exhaustive study of the available literature to specify the parameters and/or designing experiments to estimate each of the parameters as required. It is now possible, using the necessary experimental data, to use optimization tools or artificial intelligence to solve this problem [2], [25]. An approach to the ODE-based models is based on a Piecewise Linear Differential Equations (PLDEs) [3], [5], [7]. On the other hand, artificial intelligence techniques, including fuzzy logic, have been incorporated primarily to the classification and analysis of data obtained through Microarrays [8], [11], [21], [15], [23]. Moreover, the techniques of fuzzy logic have also been considered for describing biological systems of which some a priori knowledge exists [12], [18], [19].

In this context, it is necessary to propose models that attempt to get good predictions, reducing the need for prior knowledge. We must also consider that these models should have the ability to easily incorporate the knowledge of experts in the field of genomics, as well as experimental information thus complementing previous work with the new developments. Similarly, the steady states of the model should be analyzed in order to ensure a biologically acceptable description. In this work we propose the development of a model that integrates the Fuzzy Inference with Differential Equations. We have chosen the differential equations because they constitute a model that describes with sufficient fidelity the regulatory processes; we also incorporate fuzzy logic because they have the ability to work with non-linear systems. The proposed model can reduce the need for prior knowledge of the phenomenon due to the training of the network ANFIS, transforming it into a *grey box model* [1], combining differential equations, and network training. In addition, the proposed model makes it possible to express their Fuzzy Rules across linguistic labels, which gives the ability to incorporate expert knowledge in a friendly language.

1.1 Biological Background

A gene is active when it is able to synthesize one or more (depending on the body) types of proteins, which can play a regulatory role in the expression of the same or other genes, and also can catalyze chemical reactions within a cell. Therefore the function of a cell in an organism depends on the genes that are active, or in other words, it depends on the expression of its genes. The process of synthesis of a protein consists of 2 phases, the first of them is known as *transcription*. At this stage the segment of DNA that contains the information of the gene is transcribed into a string of messenger RNA (mRNA) through the enzyme called RNA polymerase. The action of this enzyme is regulated by a series of molecules called *transcription factors* (TF), which use certain areas of DNA, called zones *cis-regulatory* that are specific to this end. Then, when we have the chain of mRNA with the information on the protein synthesis it comes a second stage called *Translation*. Here an internal organelle called a *ribosome* reads the information chain mRNA and, together with the transfer RNA (tRNAs), it links the amino acids needed to form the protein that indicates the information of the gene. This protein may regulate the expression of the same or other genes, and can also participate in metabolic processes of the cell.

2 Materials and Methods

This section defines the model based on a fuzzy inference system (FIS), presenting also the characteristics of the first models based on ODEs and its piecewise linear approximations in order to compare all these models in a real system.

2.1 ODEs based Models

These models are based on a series of ordinary differential equations that relate mRNA molecules with proteins that they synthesize, the action of other molecules present in the regulation can also be incorporated. Usually this kind of differential equations presents the form:

$$\frac{dx_i}{dt} = \sum_j \alpha_{ij} f_{ij}(x_j) - \gamma_i x_i \tag{1}$$

Where x_i represents a molecule produced in the process, a_{ij} is the production rate of the molecule i due to the molecule j, γ_i is the degradation rate of the molecule i, and f_{ij} is a function that determines the interaction of the molecule x_j with the molecule x_i, which is called regulation function. This is a non-linear function, which provides for realism from a biological point of view. It is generally defined as a function of sigmoidal type, commonly the *Hill function* [3], [5]:

$$f_{ij} = h^+_{ij}(x_j, \theta_{ij}, m_{ij}) = \frac{x_j^{m_{ij}}}{\theta_{ij}^{m_{ij}} + x_j^{m_{ij}}} \tag{2}$$

This equation shows that for values x_j well over the threshold, θ_{ij}, the function tends to a value of 1, whereas when x_j tends to values below the threshold, θ_{ij}, the function is close to the value 0, as seen in Figure 1.a. The speed with which the function passes from the value 0 to 1 (while x_j varies) depends on the slope at the point threshold. This slope changes depending on the value of m_{ij}.

2.2 PLDE-Step Models

Due to the nonlinear nature of the ODEs-based models, piecewise linear approximations have emerged that attempt to simplify the ODEs-based model to a set of linear models. Such models are based on a *Piecewise Linear Differential Equations* (PLDEs). The number of potential resulting linear models depends on the amount of regulation functions to approximate and the amount of linear segments on each approximation. A widely used approach approximates the regulation function, f_{ij}, to only 2 cases:

$$f_{ij} = s_{ij}(x_j, \theta_{ij}) = \begin{cases} 1, & \text{if } x_j > \theta_{ij} \\ 0, & \text{if } x_j \leq \theta_{ij} \end{cases} \tag{3}$$

The regulation function is then approximated to a step function [1], so this model has been named *Piecewise Linear Differential Equations-Step* (PLDE-Step) [20]. In this case, the value of the threshold, θ_{ij}, is the only parameter to estimate for each regulation function. The curve is shown in Figure 1.b.

2.3 PLDE-Logoid Models

In addition to the step function, there are other features to approximate a nonlinear model to a piecewise linear. Thus, we find in the literature approaches that use the ramp function as part of the linear segments of the model [5]. This approximation of the regulation function is also known as a *logoid function* [3] calling such models as based on *Piecewise Linear Differential Equations-Logoid*(PLDE-Logoid) [20]. In this case, the curve takes the form shown in Figure 1.c, and the regulation function is defined as:

$$f_{ij} = l_{ij}(x_j, \theta_{ij}, \delta_{ij}) = \begin{cases} 1, & \text{if } x_j > \theta_{ij} + \frac{\delta_{ij}}{2} \\ \frac{1}{\delta_{ij}}(x_j - \theta_{ij}) + \frac{1}{2}, & \text{if } \theta_{ij} - \frac{\delta_{ij}}{2} < x_j \leq \theta_{ij} + \frac{\delta_{ij}}{2} \\ 0, & \text{if } x_j \leq \theta_{ij} - \frac{\delta_{ij}}{2} \end{cases} \tag{4}$$

Where the new parameter, δ_{ij}, corresponds to the piece at which the function moves from 0 to the value set to 1, corresponding to the inverse of the ramp function in that segment. As shown in (4), there are 3 possible cases for every regulation function, which increase the number of potential linear differential equations to solve compared to the model PLDE-Step. However this also increases the accuracy of the approximation.

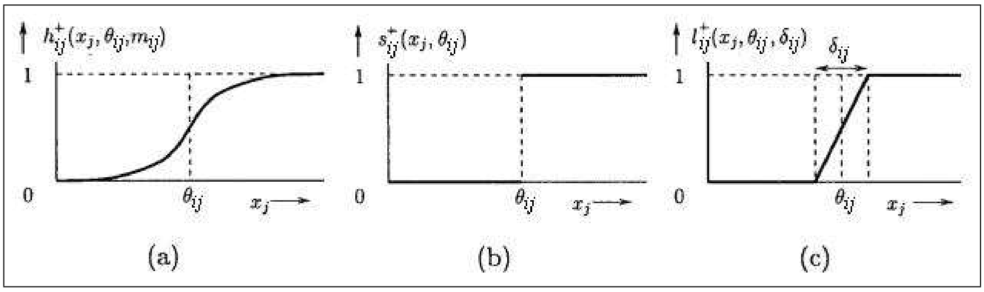

Figure 1: Different regulation function: a) the Hill function, b) Step function and c) Logoid function.

2.4 Proposed Model

In this case each regulation function is approximated by a Fuzzy Inference System (FIS), of the Takagi-Sugeno type. This FIS is capable of representing the nonlinear behavior of the regulation function making it possible to define linguistic labels to determine the concentrations of molecules. Moreover, one can assume the production rates as unknown and include their action within the FIS, which diminishes the prior knowledge required for modeling. Thus, the differential equations take the form:

$$\frac{dx_i}{dt} = \sum_j \text{fis}_{ij}(x_j) - \gamma_i x_i \tag{5}$$

By comparing (5) to (1) we observe that it has been replaced $\alpha_{ij} f_{ij}$ by the fuzzy inference system fis_{ij}, i.e. not only approaching the regulation function but also including the production rates.

For the design of the FIS it should mainly be considered the characteristics of the membership functions, the number of them, the fuzzy rules, and the output functions. The latter implies that when designing the fuzzy inference system a good knowledge of the phenomenon is required, including aspects such as the ranges of concentrations, the fuzzy rules, and so on. That is why we use a training network called ANFIS [16] to get a fuzzy system that approximates the ODEs-based model. This network is trained with experimental data and is capable of adapting, using a hybrid learning algorithm, the characteristics of membership functions and output functions so to reduce the error between the experimental data and data generated by the FIS. Figure 2, shows a fuzzy inference system with 2 inputs x and y, 2 membership functions for each input (A_1, A_2, B_1 and B_2), 2 fuzzy rules which consequences are f_1 and f_2, and 1 output f.

Among the most important factors to be considered for the training of the network are the type and number of membership functions, the maximum amount of training epochs and the error goal. We must also consider that the data for training must provide sufficient information to model the dynamics of the system. The training network allows complementing the phenomenological model with the information obtained from the experimental data. Consequently, the model is considered a hybrid model or grey box model. In this work the proposed model is called *ODE-FIS model* due to its characteristics.

2.5 Implementation in a real system

All models are compared representing the Lac Operon in E. Coli. The Lac operon is a very well studied process in the bacterium Escherichia coli [10], [22], [24], and although broadly it appears simple, in reality it can be modeled so detailed that you can include more than 100 biochemical reactions. In this paper we use the model of the lac operon shown in [24].

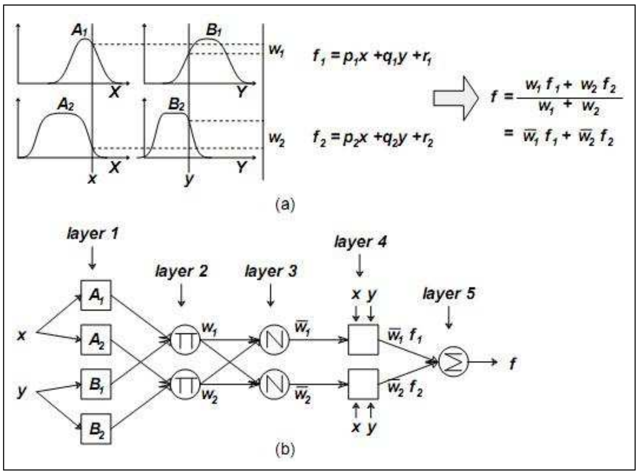

Figure 2: Structure of a ANFIS network: a) Takagi-Sugeno type Fuzzy Inference System, b) ANFIS representation of the system.

The description of the process is as follows. The main source of carbon for the bacteria E. Coli is glucose. When glucose is not present in the environment cell, the bacterium is able to form glucose through lactose. For this, there is a regulatory mechanism that allows to synthesize the enzymes necessary to obtain glucose. This mechanism is called *lac operon*. This model describes the synthesis of glucose from lactose by the bacterium E Coli. This is due to the fact that in the absence of glucose, but in the presence of lactose, the bacteria activates the synthesis of β-galactosidase and Permeases. The β-galactosidase breaks down the lactose into alolactosa, glucose and galactose, being the Alolactosa the inducer in the operon regulation. Moreover permeases allow the passage of external Lactose towards the cell. An outline of the system as used in [7], is shown in Figure 3.

The model presented in [24]is based on 5 nonlinear differential equations, where we can find 6 Hill functions. These equations describe the production of mRNA, β-galactosidase, alolactosa, lactose and permeases, also allowing to manipulate the external lactose and feed phosphate.

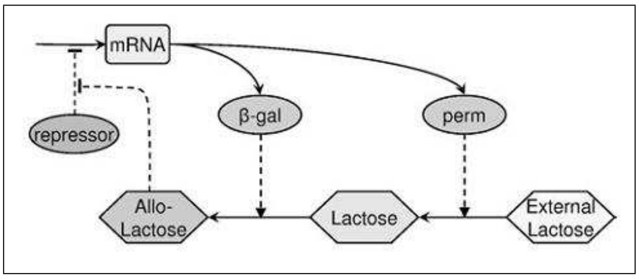

Figure 3: Simplified outline of the lac operon in E. Coli

As the model used is based on Hill functions, for comparison purposes it should be approximated by the models PLDE and ODE-FIS. In the case of PLDE-step model we use the same threshold values presented by the ODEs-based model, and therefore it does not require a new design parameter. In the case of PLDE-Logoid model the thresholds do not vary, however we must design the value δ_{ij}, shown in (4). For doing this, the coefficient k must be calculated, such that $\delta_{ij}j = k_ij$, which in turn delivers the lowest value of steady state error with respect to the ODE models. In the case of the ODE-FIS model we train 6 regulation functions with data obtained from the model shown in [24], and which entries correspond to states of the system. To cover a wide range of training conditions we reduce the external lactose concentration of 0.08 mM to 0 mM, through 4 negative steps, which in turn allows obtaining more information on the dynamics of the system. The structure of the model corresponds to 3 membership functions per entry, each one of the Gauss type, labeled *Low*, *Medium* and *High* referring to the concentration level of each entry. The training epochs are 80 and the error goal is 0.

For comparison purposes we reproduce the 2 experiments shown in [24] using the 4 models described previously. In each case, both the expression of β-galactosidase and permeases are plotted. The first of these experiments consists on monitoring the changing states of the system in time for a given set of initial conditions, and where the external lactose level and the feeding phosphate rate are kept constant. In the second experiment we maintain a constant level of external lactose changing periodically the phosphate feeding. For the comparison of β-galactosidase we also count with the experimental data [9] and [14] for the experiment 1 and data from [6]to experiment 2, which were provided by the authors of [24].

To compare, on a quantitative basis the approximations of models PLDEs and ODE-FIS, we have replicated experiment 1 and formulated a table with the steady state error (SSE) and the integrated square error (ISE) with respect to the ODEs-based model, considering a simulation time of 500. It was also implemented an experiment to assess whether the training of the network ANFIS was able to capture the main equilibrium points of the system. Thus, we performed a sweep sampling of the values of the external lactose and the initial conditions to see if the model ODE-FIS has the same equilibrium points as the ODEs model. All the experimental work is developed in the Matlab software, using primarily the Simulink, Fuzzy Logic and Optimization Toolboxes.

3 Results

In the work of Yildirim and Mackey [24] the expression of β-galactosidase for two types of experiments is presented, being reproduced for all models. The standard profile of β-galactosidase, is shown in Figure 4 for the ODEs-based model, the PLDE-Step model, the PLDE-Logoid model, the ODE-FIS model, and the experimental data of the work of [9] and [14]. It is noted that all models evolve to the same steady state except PLDE-Step, which clearly does not represent adequately the profile of β-galactosidase.

In addition to the β-galactosidase we present the dynamics of the permeases, standardized and shown in Figure 5. Once again the poor performance of the PLDE-Step model is repeated. We also stress the monitoring overshoot achieved by the ODE-FIS model.

Figure 6 shows the normalized profile of β-galactosidase for all models, in addition to the experimental work of [6]. This figure shows the similarity between the experimental data, and the ODE and ODE-FIS models, but not PLDEs models (having a lower yield), particularly the PLDE-Step model.

For the experiment 2, the permeases level is followed properly for the ODE-FIS model, as shown in Figure 7. In addition, the models PLDEs again show a poor performance.

In order to determine which of the approaches better represents the model based on ODEs we obtain error rates by simulating the experiment 1. Table 1 shows the steady state error (SSE) and the integrated square error (ISE) for a time simulation of 500.

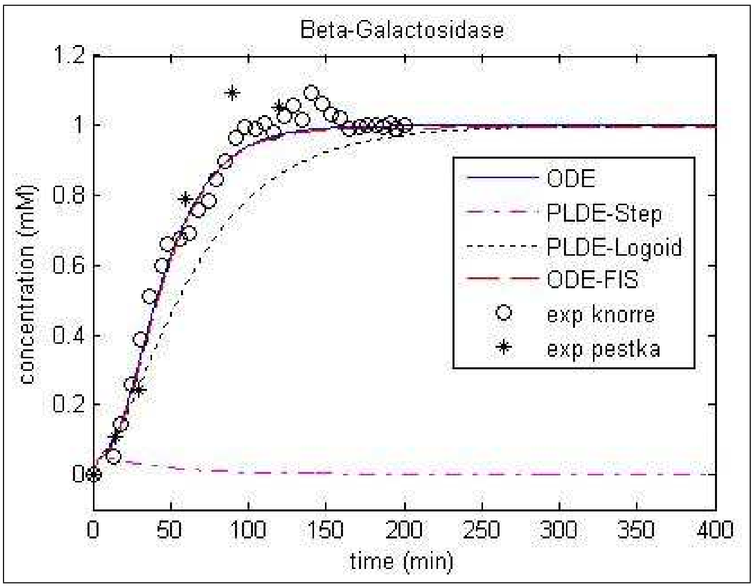

Figure 4: Comparison of the dynamics of β-galactosidase for different models depending on the conditions of the experiment 1.

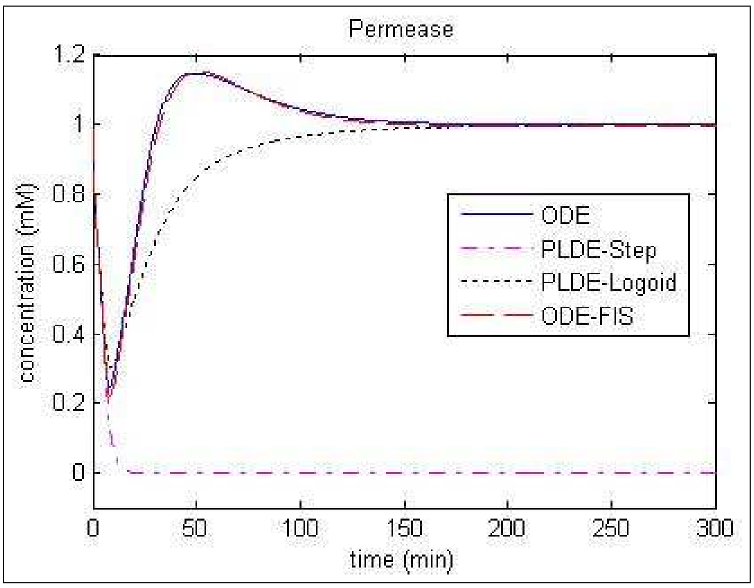

Figure 5: Comparison of the dynamics of permeases for different models depending on the conditions of the experiment 1.

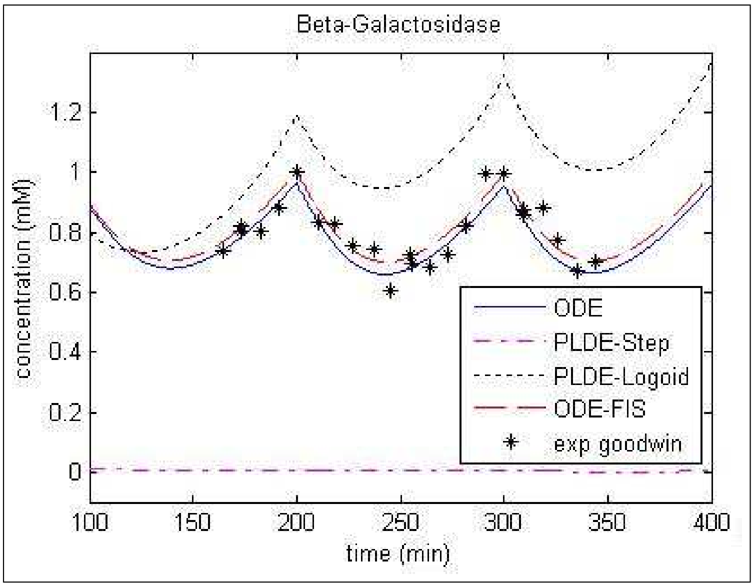

Figure 6: Comparison of the dynamics of β-galactosidase for different models depending on the conditions of the experiment 2.

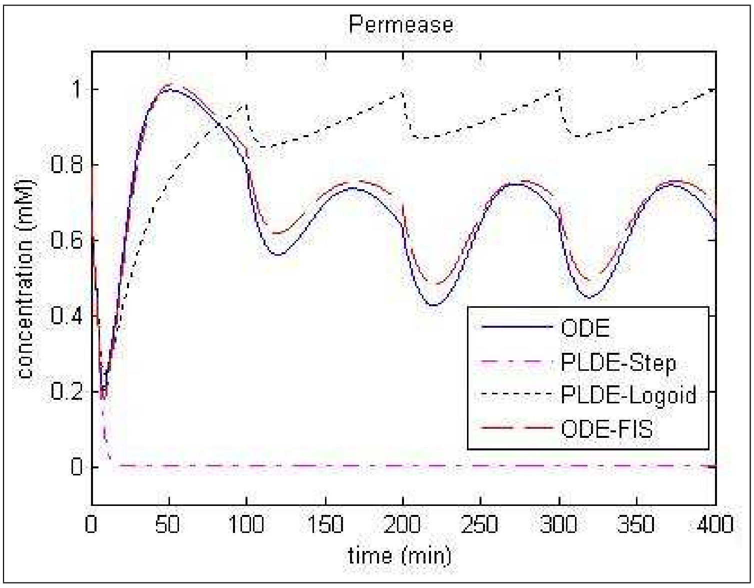

Figure 7: Comparison of the dynamics of permeases for different models depending on the conditions of the experiment 2.

	SSE		ISE	
	β-gal	Permease	β-gal	Permease
PLDE - Step	7.300 e-4	1.503 e-2	2.272 e-4	1.100 e-1
PLDE - Logoid	2.739 e-8	3.349 e-7	1.030 e-6	9.080 e-4
ODE - FIS	5.257 e-7	1.080 e-5	3.314 e-9	6.677 e-6

Table 1: Steady state error with respect to ODEs model

To demonstrate the use of rules and linguistic labels we mention the case of a term describing the behavior of the alolactosa, which depends on 2 inputs; internal lactose (L) and β-galactosidase (B). Given that we define 3 fuzzy sets (*Low*, *Medium*, *High*), there are 8 possible rules (2^3) that connect the 2 inputs. As an example we mention 3 rules that were obtained from the training process:

R1-*If L is High and B is Low then the influence of the term is null*

R2-*If L is Medium and B is Low then the influence of the term is null*

R3-*If L is Low and then B is Low then the influence of the term is null*

The label *null* is associated to the output function of the Takagi-Sugeno system, and corresponds to a value of 0. When analyzing these rules we observe that if the concentration of β-galactosidase is low, the associated term does not influence the production of alolactosa, which is consistent with reality. Due to the fact that these 3 rules depend mainly on the value of B, they can be edited and replaced by a single one having the form:

R- *then the influence of the term is null*

In addition to editing rules, you can edit the features of the membership functions. The toolbox of Matlab allows you to graphically edit the membership functions, without the need of a detailed mathematical knowledge of these functions. In addition, using Simulink you can see the level of activation of each rule and the degree of membership of the states in the fuzzy sets in the inference systems, all this while the simulation takes place.

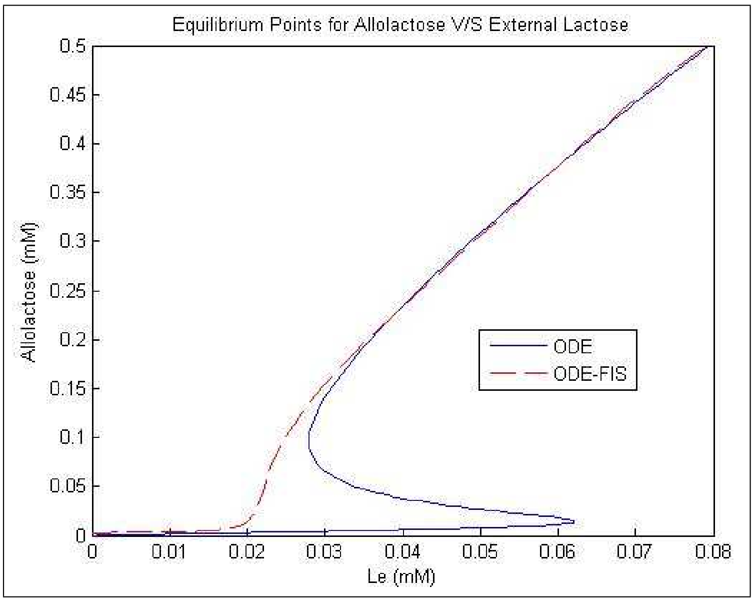

Figure 8: Equilibrium points of ODEs model and its comparison with the equilibrium points found for ODE-FIS model.

With regards to the stability of the ODE-FIS model, Figure 8 shows the equilibrium points for Alolactosa as external lactose level, as shown in [24]. Additionally the figure also shows the steady states of the ODE-FIS model. Most of the equilibrium points of ODEs model are also equilibrium points of the ODE-FIS model. It must be noticed that for each value of the external lactose in the ODE-FIS model we do not see more than 1 equilibrium point. On the contrary, in the ODEs model we find up to 3 points.

4 Summary and Conclusions

The flexibility that delivers the fuzzy logic and the capacity of training provided by ANFIS allowed to represent the non-linear system behaviour with enough similarity to the obtained with ODE, showing a better performance than the PLDE models, even without describing the dynamic transient problems of interacting molecules. It should be mentioned that the PLDE models can be enhanced with optimization techniques and/or artificial intelligence tool to better design parameters θ_{ij} and δ_{ij} as needed. However this requires additional algorithms, not necessarily trivial. The ANFIS network allowed to obtain (from the training data) all the information needed to describe not only the transient state of the performed experiments, but also was able to achieve a large quantity of stable points of ODEs. This shows the great training capacity of the network, and the flexibility of the fuzzy inference system.

The fuzzy logic has proved to be an important tool due to its ability to represent non-linear systems, its friendly language to express knowledge and the ability to incorporate and edit fuzzy rules. In addition, complementing the fuzzy logic with an artificial neural network for training (ANFIS) turns to be a powerful tool for obtaining knowledge from experimental data, suggesting the development of new techniques based both on fuzzy logic as in the networks of training and differential equations. The natural step now is to work with larger regulatory networks, adressing the criteria for modeling them in such a way to obtain an acceptable representation of biological phenomena without compromising the viability of its computational implementation, while striving to maintain a simple and understandable language that allows systems analysis from a qualitative perspective.

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An Immuno-Genetic Hybrid Algorithm

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Abstract: The construction of artificial systems by drawing inspiration from natural systems is not a new idea. The Artificial Neural Network (ANN) and Genetic Algorithms (GAs) are good examples of successful applications of the biological metaphor to the solution of computational problems. The study of artificial immune systems is a relatively new field that tries to exploit the mechanisms of the natural immune system (NIS) in order to develop problem- solving techniques. In this research, we have combined the artificial immune system with the genetic algorithms in one hybrid algorithm. We proposed a modification to the clonal selection algorithm, which is inspired from the clonal selection principle and affinity maturation of the human immune responses, by hybridizing it with the crossover operator, which is imported from GAs to increase the exploration of the search space. We also introduced the adaptability of the mutation rates by applying a degrading function so that the mutation rates decrease with time where the affinity of the population increases, the hybrid algorithm used for evolving a fuzzy rule system to solve the well-known Wisconsin Breast Cancer Diagnosis problem (WBCD). Our evolved system exhibits two important characteristics; first, it attains high classification performance, with the possibility of attributing a confidence measure to the output diagnosis; second, the system has a simple fuzzy rule system; therefore, it is human interpretable. The hybrid algorithm overcomes both the GAs and the AIS, so that it reached the classification ratio 97.36, by only one rule, in the earlier generations than the two other algorithms. The learning and memory acquisition of our algorithm was verified through its application to a binary character recognition problem. The hybrid algorithm overcomes also GAs and AIS and reached the convergence point before them.
Keywords: genetic algorithms, artificial immune system, fuzzy logic, breast cancer diagnosis, memory acquisition.

1 Introduction

Computing and engineering have been enriched by the introduction of the biological ideas to help developing solutions to various problems. This can be exemplified by the Artificial Neural Networks (ANN), Evolutionary Algorithms (EA) [11], Artificial Life (ALife), and cellular automata (CA) [13]. There exist three different approaches; the first is: biologically motivated computing, under this umbrella the EA, ANN and artificial immune system (AIS) [21]; the second is computationally motivated biology, where computing provides models and inspiration for biology (i.e. ALife and CA). The third approach is computing with biological mechanisms, which involves the use of information processing capabilities of biological systems to replace or supplement the current silicon-based computers (e.g. Membrane computing, Quantum computing and DNA computing) [8], [9] [14], [18]. Our research point will be under the umbrella of the first approach.

In this paper, we combine two methodologies which are Genetic Algorithms and Artificial Immune System (AIS), so as to automatically produce a fuzzy system for breast cancer diagnosis. The major advantage of fuzzy systems is that they favor interpretability [3], [4] and provide what is called confidence measure which means, in our case, the degree of benignity or malignancy. Finding good fuzzy systems is quite a hard task. So, this is where GA and AIS algorithms work, enabling the automatic production of fuzzy systems, based on a database of training cases.

In this paper we also ensure the ability of memory acquisition and learning of the algorithm by applying it to a binary pattern recognition problem.

The paper is organized as follows: in the next two sections we provide an overview of the clonal selection algorithm and the genetic algorithm. In section [4] we present our proposed hybrid algorithm between GA and AIS that will be tested on the Wisconsin Breast Cancer Diagnosis (WBCD) problem described in section [5]. Evolving fuzzy system of the WBCD, parameters setup and testing also included in section [5]. Section [6] speaks about the learning and memory acquisition of the hybrid algorithm. The algorithm testing is delineated also in section [6], followed by concluding remarks in Section [7].

2 The clonal selection algorithm

The standard clonal selection algorithm CLONALG [5], [6], [15], [16], [17] can be summarized as follows.

```
Begin
    t=0;
    Initialize the initial population p(t) randomly;
    Identify antigen S;
    Evaluate affinity p(t)versus S;
    While (not finished) do
        Begin
            t= t+1;
            Select C(t) from p(t-1);
            Proportional cloning of C(t) forming C'(t);
            Mutation C'(t) forming c"(t);
            Select P(t) from c"(t) and P(t-1);
            Select memory cell from P(t);
            Metadymanics;
        End.
End.
```

3 The genetic algorithm (GA)

The standard genetic algorithm [7], [23] can be summarized as follows.

```
Begin
    t=0;
    Initialize the initial population p(t) randomly;
    Evaluate structures in p (t);
    While (not finished) do
        Begin
            t= t+1;
            Select parents C(t) from p(t-1);
            Crossover and mutate structures in C (t) forming C' (t);
```

```
            Replace C' (t) by P (t-1);
        End.
End
```

4 The proposed hybrid algorithm

$$D = \sum_{i=1}^{L} \delta \quad where \begin{Bmatrix} 1, & ab_i \neq ag_i \\ 0, & otherwise \end{Bmatrix} \tag{1}$$

The affinities of individuals are measured using the hamming distance depicted in equation 1.

The proposed algorithm modifies clonal selection algorithm mutation method. The mutation in nature occurs at small percentage value = 0.002 and this is rational from the computational point of view to ensure that the good solutions are not distorted too much. However, researches have shown that an initial large mutation rate that decreases exponentially as a function of the generation number improves the convergence speed and accuracy [1].

The initial large mutation rate ensures that a large space is covered, while the mutation rate becomes smaller when the individuals start to converge to the optimum. This is accepted solution for the trade off between the exploration and exploitation We used the time-decaying formula in equation (2) [18], [22], [24] where τ is a positive constant, $m(0)$ is the initial large mutation rate and t is the generation number. The equation is depicted in Figure 1. We have imported the crossover operator from the genetic algorithms in order to increase the exploration of the landscape and to add a recombination operator in the clonal selection algorithm.

$$m(t) = m(0)e^{-t/\tau^2} \tag{2}$$

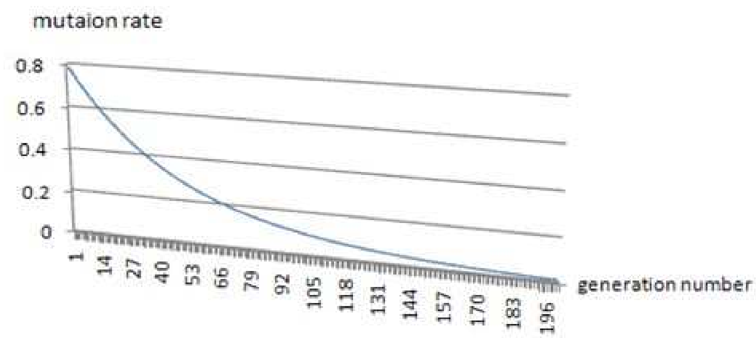


Figure 1: The effect of the degraded function on mutation value

The proposed algorithm can be summarized as follows.

```
Begin
    t=0;
    Initialize the initial population p(t) randomly;
    Identify antigen S;
    Evaluate fitness p (t) versus S;
    While (not finished) do
        Begin
            1.  t= t+1;
            2.  Select C(t) from p(t-1);
            3.  Proportional cloning of C(t) forming C'(t);
```

Table 1: The WCBD data representation

case	V_1	V_2	...	V_9	Diagnosis
1	1	2	...	8	Benign
2	2	4	...	3	Benign
...	...	...	...	...	...
683	4	8	...	1	Malignant

```
            4.  Degraded Proportional Mutation C'(t) forming c"(t);
            5.  Crossover c"(t) forming C*(t);
            6.  Select P(t) from c*(t) and    P(t-1);
            7.  Select memory cell from P(t);
            8.  Metadymanics;
        End.
End.
```

The proposed algorithm will be tested on the famous Wisconsin breast cancer diagnosis problem (Section 5) and simple binary pattern recognition problem (Section 6) to ensure the memory acquisition ability of the algorithm.

5 The Wisconsin breast cancer diagnosis problem

In this section, we present the Wisconsin breast cancer diagnosis problem [3] which is the test case of our proposed algorithm. Breast cancer is the most common cancer among women, excluding skin cancer. The presence of a breast mass is an alert sign of a cancer, but it does not always indicate a malignant one. Fine Needle Aspiration (FNA) is an outpatient procedure that involves using a small-gauge needle to extract fluid directly from a breast mass. FNA procedure over breast masses is a cost-effective, non-traumatic, and mostly non-invasive diagnostic test that obtains information needed to evaluate malignancy. The Wisconsin Breast Cancer Diagnosis (WBCD) database [4] is the result of the efforts made at the university of Wisconsin Hospital for accurately diagnosing breast masses based solely on an FNA test. Nine visually assessed characteristics of an FNA sample considered relevant for diagnosis were identified, and assigned an integer value between 1 and 10. The measured variables are as follows:

1. Clump thickness (V_1);
2. Uniformity of cell size (V_2);
3. Uniformity of cell shape (V_3);
4. Marginal adhesion (V_4);
5. Single epithelial cell size (V_5);
6. Bare nuclei (V_6);
7. Bland chromatin (V_7);
8. Normal nucleoli (V_8);
9. Mitosis (V_9).

The database itself consists of 683 cases. The general form of the database is described in Table 1. There exist some previous systems that achieved high classification ration, but these systems look like black boxes and with no explanation or interpretation about how the decision was taken. Further, the degree of benignity or malignancy is not provided. These two points are covered in this study besides high performance classification ratio.

5.1 Evolutionary fuzzy modeling

Evolutionary algorithms are used to search large, and often complex, search spaces. They have proven worthwhile on numerous diverse problems and are able to find near-optimal solutions with an adequate performance measure. Fuzzy modeling can be seen as an optimization problem where part or all of the parameters of a fuzzy system constitute the search space.

5.2 Applying evolution to fuzzy modeling

Three of the four types of fuzzy parameters can be used to define targets for evolutionary fuzzy modelling: structural parameters, connective parameters, and operational parameters. Logical parameters are usually predefined by the designer based on experience.

The evolutionary algorithm is used to tune the knowledge contained in the fuzzy system by finding membership function values (p, d values) and the relevant variables. Evolutionary structure learning is carried out by encoding within the genome an entire fuzzy system. This is known as the Pittsburgh approach.

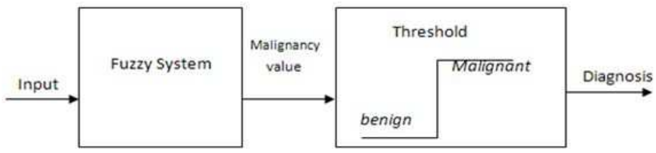


Figure 2: The proposed diagnosis system. Note that the fuzzy subsystem displayed to the left is the fuzzy inference system in Figure 3.

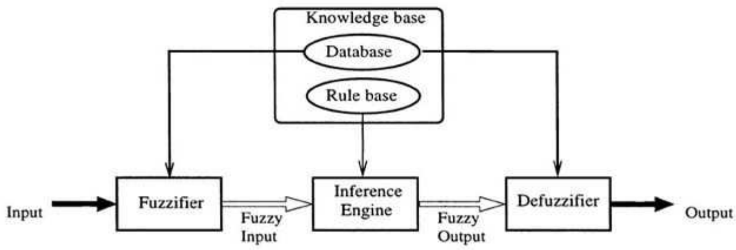


Figure 3: Basic structure of a fuzzy inference system

5.3 Evolving fuzzy systems for the WBCD problem

The solution scheme we propose for the WBCD problem is depicted in Figure 2, Note that the fuzzy subsystem displayed to the left of figure 2 is the fuzzy inference system of Figure 3 [10], [20]. Figure 2 consists of a fuzzy system and a threshold unit. The fuzzy system computes a malignancy value of the malignancy of a case, based on the input values, the threshold unit then outputs a benign or malignant diagnostic according to the fuzzy system's output. If the malignancy value is less than or equals 3, it is considered a benign case. Other than that, it is diagnosed as a malignant one.

5.4 Fuzzy system parameters

According to information obtained from previous work [3], we have deduced the following points.

- Small number of rules: Systems with no more than four rules have been shown to obtain high performance [2], [19].
- Small number of variables: Rules with no more than 4 antecedents have proven to be adequate[2].
- Nature of the input variables: higher-valued variables are associated with malignancy. Some fuzzy models forgo interpretability in the interest of improved performance. Where medical diagnosis is concerned, interpretability, also called linguistic integrity, is the major advantage of fuzzy systems. This motivated us to take into account the following semantic criteria, defining constraints on the fuzzy parameters [12]:
- Distinguishability: To what extent the system is understood and has interpretability.
- Justifiable number of elements: The number of membership functions of a variable. This number should not exceed the limit of 7 ± 2 distinct terms. The same criterion is applied to the number of variables in the rule antecedent; this is to be familiar for humans.
- Orthogonality. For each element of the universe of discourse, the sum of all its membership values should be equal to one.

5.5 The fuzzy system setup

Logical parameters

- Reasoning mechanism: singleton-type fuzzy system, i.e. Output membership functions are real values, rather than fuzzy ones.
- Fuzzy operators: min.
- Input membership function type: orthogonal, trapezoidal.
- Defuzzification method: weighted average.

Structural parameters

- Relevant variables: there is insufficient a priori knowledge to define them; therefore, this will be one of the algorithm's objectives.
- Number of input membership functions: two membership functions denoted Low and High.
- Number of output membership functions: two singletons are used, corresponding to the benign and malignant diagnostics.
- Number of rules: in our approach, this is a user-configurable parameter. Will there be only one rule? The rule itself is to be found by the genetic algorithm.

Connective parameters

- Antecedents of rules: to be found by the algorithm.
- Consequent of rules: the algorithm finds rules for the benign diagnostic; the malignant diagnostic is an else condition.
- Rule weights: active rules have a weight of value 1 and the else condition has a weight of 0.25.

Operational parameters

- Input membership function values: to be found by the evolutionary algorithm.
- Output membership function values: following the WBCD database, we used a value of 2 for benign and 4 for malignant.

5.6 The evolutionary algorithm setup

We apply Pittsburgh-style structure learning, using our algorithm to search for three parameters. The relevant variables, the input membership function values, and the antecedents of rules. They are constructed as follows:

- Membership function parameters. There are nine variables (V_1-V_9), each with two parameters P and d, defining the start point and the length of the membership function edges, respectively.
- Antecedents. The i^{th} rule has the form: **if** (V_1 is A_1^i)**and...and** (V_9 is A_9^i) **then** (output is benign) where A_j^i represents the membership function applicable to variable V_j. A_j^i can take the values: 1 (Low), 2 (High), or 0 or 3 (Other).
- Relevant variables are searched for implicitly by letting the algorithm choose non-existent membership functions as valid antecedents; in such a case, the respective variable is considered irrelevant.

Table 2: Parameters encoding of a genome, total genome length is 54+18= 72

Parameter	Values	Bits	Quantity	Total bits
P	1-8	3	97	27
d	1-8	37	9	27
A	0-3	2	9	18

The parameters encoding are described in Table 2, which form a single individual's genome. Table 3 shows a sample genome. We used a genetic algorithm with a fixed population size of 200 individuals to evolve the fuzzy inference system, and fitness-proportionate selection. The algorithm terminates when the maximum number of generations is reached.

An example of a genome for a rule system depicted in table 3, The first 18 positions encode the parameters P and d for the nine variables V_1 -V_9. The rest encode the membership function applicable for the nine antecedents of the rule; table 4 is an interpretation of the database and the rule base of the rule system encoded in table 3.

5.7 Testing

The proposed algorithm has been tested on the WSBC problem. The three algorithms have been implemented and have been tested in Wisconsin database. The three algorithms have reached a valid classification ratio equal to 97.36% i.e. 665 valid diagnosis cases from 683 cases. And the results of the three algorithms were depicted in Figure 4. It is clear that the hybrid algorithms reached the maximum classification ratio in the earlier generations before the GA and the AIS. Also the AIS reached before the GA.

Table 3: Database

p_1	d_1	p_2	d_2	p_3	d_3	p_4	d_4	p_5	d_5	p_6	d_6	p_7	d_7
3	5	4	1	2	8	5	1	7	7	2	5	5	5
p_8	d_8	p_9	d_9	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	
7	2	4	7	1	1	3	3	3	1	3	1	1	

Table 4: Rule Base

Rule	If ((v_1 is low) and (v_2 is low) and (v_6 is low) and (v_8 is low) and (v_9 is low)) then(output is benign)
Default	Else(output is malign)

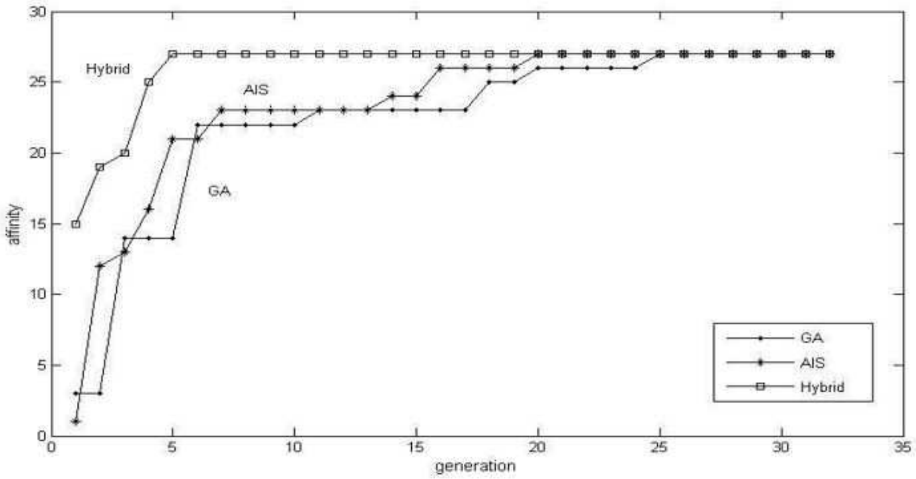


Figure 4: The execution of the three algorithms

6 The Pattern Recognition Problem

The learning and memory acquisition was verified through its application to a binary character recognition problem. In this case, we assumed that the antigen population was represented by a set of ten binary characters (N = 10) to be learned. Each character is represented by a bit string of length L = 121. The population size =200.

The original characters are depicted in Figure 5. Figure 6 illustrates the initial memory set. Figure 7 illustrates the input patterns. (i.e. the antigens) for which the learning will takes place. Figures 8,9 and 10 represent the maturation of the memory set through 200 generations. The affinity here refers the degree of matching of the antigens, i.e. the affinity measure is the hamming distance (discussed in Section 4) between the antigens and antibodies, the. Note that the exact matching is not important for recognition; partial matching is enough. The hybrid algorithm converged at generation 200.

Figure 8, 9 and 10 presents the application of the GA, AIS and the hybrid algorithm to the binary character recognition problem respectivily where (a) presents Memory set after 50 cell generations; (b)

Figure 5: The original digits

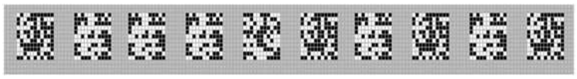
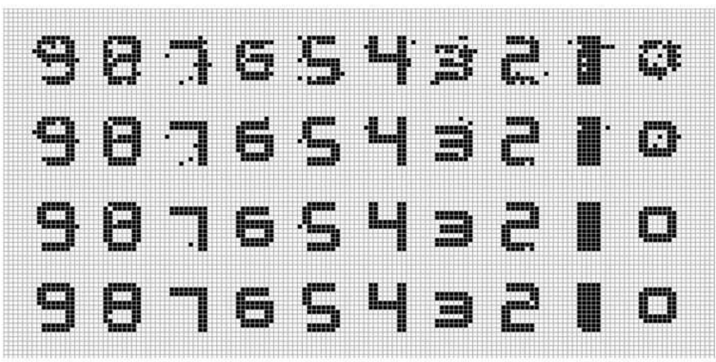


Figure 6: The initial input patterns

Figure 7: The input patterns (i.e. the antigens) for which the learning will take place

(a)
(b)
(c)
(d)

Figure 8: Application of the GA to the binary character recognition problem



(a)
(b)
(c)
(d)

Figure 9: Application of the AIS to the binary character recognition problem

Figure 10: Application of the Hybrid Algorithm to the binary character recognition problem.

presents Memory set after 100 cell generations; (c) presents Memory set after 150 cell generations and (d) presents Memory set after 200 cell generations.It is clear that the hybrid algorithm overcomes the other two algorithms. We have used static mutation values, also proportional to affinity, in the binary recognition problem because results showed that static mutation is better than dynamic one. Figure 11 represents the affinity of GA, AIS and the Hybrid algorithms in recognition of the pattern zero, note that the affinity refers the degree of matching with antigens. I.e. the hamming distance with antigens.

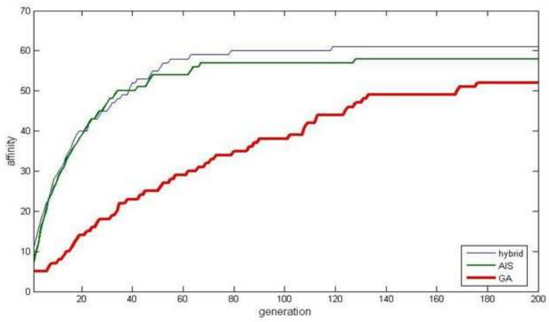


Figure 11: the affinity of GA, AIS and the Hybrid algorithms in recognition of the pattern zero

7 Conclusions

In this research, artificial immune system is combined with genetic algorithms in one hybrid algorithm. A modification is proposed to the clonal selection algorithm which is inspired from the clonal selection principle and affinity maturation of the human immune responses. The adaptability of the mutation rate is introduced by simple degrading function. Also, the crossover is merged into the clonal selection algorithm, two-point crossover applied after the mutation process, to increase the exploration of the landscape. The hybrid algorithm is combined with fuzzy logic and applied to the well-known Wisconsin breast cancer diagnosis problem. We claim that our evolved system exhibits two important characteristics; first, it attains high classification performance, with the possibility of attributing a confidence measure to the output diagnosis; second, the system has a simple fuzzy rule system; therefore, it is interpretable. The hybrid algorithm overcomes both the genetic algorithm and the artificial immune system and reached the highest classification ratio 97.36, by only one rule, in the earlier generations than the two other algorithms.

The proposed system also applied to a binary character recognition problem. The mutation in the hybrid algorithm was adapted using a degraded function so that the mutation decreases with time, but in the binary character recognition problem, the results showed that it is better to keep the mutation value small and static through all generations. The hybrid algorithm overcomes the other two algorithms.

The hybrid system can solve the WBCD problem with more than one fuzzy rule. This is to increase the classification accuracy. Also, there are many gene representation techniques that can be used instead of the Pittsburgh approach like the Michigan approach, the iterative rule learning approach and hybridization between them. This can be considered as a future work. We claim that our hybrid algorithm is highly effective and better than GAs and AIS, for sure not in all cases, future experiments may prove that GAs or AIS separately is better, but at least in memory acquisition, the WCDB and similar problems we claim that our algorithm is better.

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High Performance Computing Systems with Various Checkpointing Schemes

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Abstract: Finding the failure rate of a system is a crucial step in high performance computing systems analysis. To deal with this problem, a fault tolerant mechanism, called checkpoint/restart technique, was introduced. However, there are additional costs to perform this mechanism. Thus, we propose two models for different schemes (full and incremental checkpoint schemes). The models which are based on the reliability of the system are used to determine the checkpoint placements. Both proposed models consider a balance of between checkpoint overhead and the re-computing time. Due to the extra costs from each incremental checkpoint during the recovery period, a method to find the number of incremental checkpoints between two consecutive full checkpoints is given. Our simulation suggests that in most cases our incremental checkpoint model can reduce the waste time more than it is reduced by the full checkpoint model. The waste times produced by both models are in the range of 2% to 28% of the application completion time depending on the checkpoint overheads.
Keywords: Large-scale distributed system, reliability, fault-tolerance, checkpoint/restart model, HPC

1 Introduction

High performance computing (HPC) systems are used to address many challenging computational problems. However, an HPC system is not required only to solve these problems, but also to solve them in a short time. This requirement drives the physical size of an HPC system larger. The reliability of a large HPC system is inversely proportional to its size. For example, the Blue Gene/L system hosted at Lawrence Livermore National Laboratory (LLNL), the world second fastest HPC system, has a failure rate of roughly one failure a week [1]. Unfortunately, handling the reliability of such large HPC systems is still problematic. A Checkpoint/Restart mechanism is widely used to deal with the high failure rate problem. If a failure occurs while an application is running, the portion of the application that has been already computed has to be re-computed again. The checkpoint mechanism is able to reduce this re-computing time of an application after a failure occurrence. However, there is an additional time that is spent to perform the mechanism. The detailed of the checkpoint mechanism will be provided in Section 2.1.

Since the Message Passing Interface (MPI) is one of the most popular parallel programming paradigms, we target our reliability study on the system using the MPI standard [20]. Normally, an MPI application is decomposed and executed among a group of nodes, where individual subtasks communicate through the MPI. Because of the static view of an MPI environment [17], a single node failure would cause the whole application to fail and requires an application restart. The checkpoint/restart scheme has been widely used in [2], [4], [7], [20] to address application outages. However, applications are practically checkpointed without considering the probability of failures. As such, some checkpoints are useless because, at the checkpoint time, the chance of a failure occurrence is small. Thus, it causes unnecessary checkpoint overhead. On the other hand, the re-computing time is large because applications are not checkpointed when the probability of failure is high. Ideally, a checkpoint is needed when a failure is going to occur within a certain period of time, so there are no useless checkpoints and expensive re-computing time. So we define the waste time of the checkpoint mechanism as the sum of checkpoint overhead, re-computing time and recovery time. Consequently, we aim to minimize the waste time by balancing the checkpoint overhead and the re-computing time.

In existing studies, the optimal checkpoint placement strategy is either based on the cost function models [2], [3], [20] or Markov availability models [5], [14], [19], [22]. In addition, it is typically assumed that the system failure is a Poisson process (with a fixed failure rate). However, in practice, the system failure may not always follow the Poisson model [16] and the overall system reliability is more complex than that of its individual components.

In this paper, we propose two stochastic models for improving the checkpoint/restart scheme in an HPC environment by reducing the waste time. The reliability function of the system is obtained by analyzing historical failure data from the system event log files.

2 Full Checkpoint/Restart Model

2.1 Behavior of Full Checkpoint/Restart Model

A full checkpoint/restart mechanism is a traditional checkpoint/restart mechanism which occasionally saves running application states to a local storage. After a failure occurs, the application can be recovered from the last saved state rather than from the starting point. This results in decreasing the time that is spent to re-compute the application. Conversely, there is an additional time to save the application states which is called the checkpoint overhead. To improve the checkpoint mechanism, checkpoints should not be performed too frequently, in such a way to balance of the checkpoint overhead and the application re-computing time. Thus, we focus on how to determine checkpoint placements or intervals that minimize the waste time.

In this section, we present a checkpoint/restart model with the re-computing time coefficient for fault-tolerant parallel applications. We assume that the application model is MPI and supports a coordinated checkpoint mechanism. The characteristic of the model is directly related to the system reliability function where one of the node outage will result in an application outage because of the MPI standard. For a parallel application, the coordinated checkpoint protocol guarantees that the checkpoint of an HPC system, resulted by the synchronization of the local checkpoint on individual process, is consistent. As a result, each process is checkpointed at almost the same time, so we assume that there is no time difference for each individual process checkpoint, and treat it as a single checkpoint.

We consider a failure model that allows more than one failure during the lifetime of a given application. Moreover, after each failure, the application will be restarted from the last checkpoint. Our checkpoint/restart model is shown in Figure 1. It follows a renewal reward process in which ω_i denotes the i^{th} time between failures in each repeated cycle. We assume that the waste time (checkpoint overhead, recovery time, and re-computing time) of each cycle is a random variable, $W_1, W_2, W_3...$, since it depends on when a failure occurs. Hence, the total waste time may be expressed as

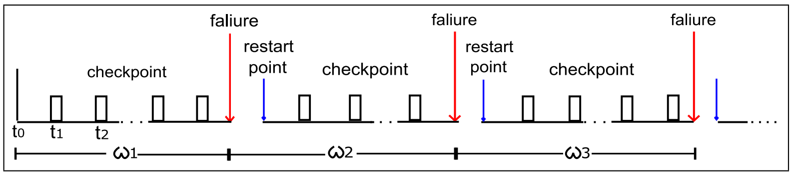

Figure 1: Checkpoint/restart as a stochastic renewal reward process

$$C_t = \sum_{i=1}^{m} W_i, \tag{1}$$

where $m = \max\{n \in \{1, 2, 3, ...\} | (\sum_{i=1}^{n} \omega_i) \leq t\}$, and C_t is called a renewal reward process.

From [15] the theorem of a renewal reward process is given as

$$\lim_{t\to\infty} \frac{E[\sum_{i=1}^{m} W_i]}{t} = \frac{E[W_1]}{E[\omega_1]} \tag{2}$$

In the checkpoint/restart model, Eq.(2) shows that the mean of the overall waste time (left hand side of the equation) can be expressed as a function of the mean waste time of the 1^{st} cycle. This means that minimizing the overall time lost is equivalent to minimizing the waste time in the 1^{st} cycle.

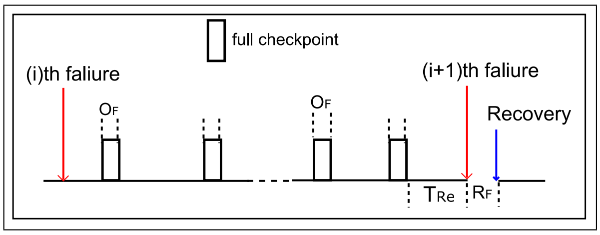

Figure 2: Checkpoint/restart as a stochastic renewal reward process

Table 1: Parameters of the Checkpoint/Restart Model

Parameters	Meaning
O_F	Checkpoint Overhead
R_F	Recovery Time
T_{Re}	Re-computing Time
$n_F(t)$	Checkpoint frequency function of the full checkpoint model
$f(t)$	Probability density function of TBF
ω_i	The cycle between failure i and failure (i+1)

Consider a checkpoint restart scheme in the first cycle ω_1 (time between two failures). Figure 2 illustrates the model with parameters such as checkpoint overhead O_F (time that is spent to save an application state), recovery time R_F (time that is spent to load the application saved state) and re-computing time T_{Re}. Through the rest of the paper, our failure model is based on the following assumptions:

1. A running application may be interrupted by a series of random transient failures where the time between failures has a certain probability density function (PDF), $f(t)$.

2. The system failure can be detected by a monitoring mechanism, and we assume that there is no failure during the re-computing and recovery time.

3. Each checkpoint overhead O_F is a constant. In practice, we can take this constant to be the average value of multiple checkpoint overheads.

4. The application can be recovered from the last checkpoint. This implies that the re-computing time T_{Re} is a period between the last checkpoint and the present failure.
5. The recovery time R_F is a constant.

Remark: Assumption 2 is satisfied since a well-managed system can be engineered with an efficient mechanism to immediately detect the failure. Assumption 5, R_F, is satisfied if there is a mechanism in place to replace the failed node with a spared node.

The objective of this model is the capability of giving the best checkpoint placement sequence that minimizes the total waste time

Definition 1. Let the sequence of discrete checkpoint placements be $0 = t_0 < t_1 < ... < t_n$, and let $n_F(t)$ be the checkpoint frequency function for the full checkpoint model defined by: $\int_a^b n_F(t)dt$ =the number of checkpoints from time a to time b. We then can imply that $\int_{t_i}^{t_{i+1}} n_F(t)\,dt = 1$.

In Figure 2, the waste time W_i (checkpoint overhead, re-computing time, and recovery time) in a given cycle ω_i can be expressed as

$$W_i = O_F \int_0^{\omega_i} n_F(\tau)\,d\tau + T_{Re} + R_F \tag{3}$$

From assumption 5, R_F is a constant, and, from assumption 5, we suppose that the system can be successfully recovered from the last checkpoint. The relationship between re-computing time T_{Re} and checkpoint interval is illustrated in Figure 3.

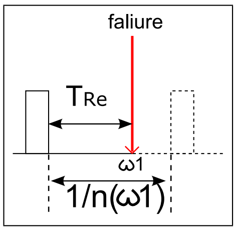

Figure 3: The relationship between rollback T_{Re} and checkpoint interval

Ling et al. [9] and Ozaki et al. [11] considered the recovery cost including both re-computing time and recovery time similar to those in our model. They represented their recovery cost by a function, called the recovery cost function. Moreover, they illustrated their model with respect to recovery cost by assuming the recovery function to be linear. Assuming linearity may be restrictive and may not lead to optimality. In our model, we consider a re-computing time coefficient k $(0 < k < 1)$ instead of a recovery cost function and propose an algorithm (end of Section 2.2) to estimate this re-computing time coefficient. The re-computing time coefficient is general and can be determined for any system failure distribution. This makes our approach useful for application purposes.

Since ω_i is the value between these checkpoint placements, by the Mean Value theorem, we can estimate the frequency of this interval by $n_F(\omega_i)$. Therefore, T_{Re} can be approximated by Eq.(4), where k is a re-computing time coefficient variable between (0,1), as seen in Figure 3.

$$T_{Re} \approx k/n_F(\omega_i), k \in (0,1) \tag{4}$$

Replacing T_{Re} in Eq.(3) by its value from Eq.(4) gives:

$$W_i = O_F \int_0^{\omega_i} n_F(t)\,dt + \frac{k}{n_F(\omega_i)} + R_F \tag{5}$$

According to the theorem of a renewal reward process in Eq.(2), the total waste time in the checkpoint and recovery process can be minimized by minimizing $E(W_1)$. Let $f(t)$ be the probability density function of time between failures. Then, the probability that the system fails in the interval $[t, t+\Delta t]$ is $f(t)\cdot\Delta t$. The expected waste time during a cycle in the checkpoint/restart process is

$$E[W_1] = \int_0^{\infty} \left(O_F \int_0^{t} n_F(\tau)\,d\tau + \frac{k}{n_F(t)} + R_F \right) \cdot f(t)\,dt. \tag{6}$$

Our interest is in determining the optimal checkpoint frequency $n(t)$ in order to minimize the expected waste time as defined by Eq.(6).

Solution: Letting $x(t) = \int_0^t n_F(\tau)\, d\tau$, then $x'(t) = n_F(t)$ and Eq.(6) becomes

$$E[W_1] = \int_0^\infty \left(O_F \cdot x(t) + \frac{k}{x'(t)} + R_F \right) \cdot f(t)\, dt. \tag{7}$$

Let $\Phi(x, x', t) = \left(O_F \cdot x(t) + \frac{k}{x'(t)} + R_F \right) \cdot f(t)$.

In order to have an extremum, the necessary condition for Eq.(7) requires that the variation of $E[W_1]$ (the first derivative regarding to the function x of $E[W_1]$) to vanish. Consequently, the function Ô must satisfy the Euler's equation as the following [6].

$$\frac{\partial \Phi}{\partial x} - \frac{d}{dt} \cdot \frac{\partial \Phi}{\partial x'} = 0. \tag{8}$$

Since $\frac{\partial \Phi}{\partial x} = O_F \cdot f(t)$ and $\frac{\partial \Phi}{\partial x'} = -\frac{k \cdot f(t)}{(x'(t))^2}$, Eq.(8) becomes:

$$O_F \cdot f(t) + \frac{d}{dt} \cdot \frac{k \cdot f(t)}{(x'(t))^2} = 0 \tag{9}$$

By integrating from 0 to t Eq.(9) on both sides, the result is:

$$O_F \cdot F(t) + \frac{k \cdot f(t)}{(x'(t))^2} = C \tag{10}$$

Since $\lim_{t \to \infty} F(t) = 1$ and $\lim_{t \to \infty} f(t) = 0$, $C = O_F$. Moreover, $x'(t) = n_F(t)$, then we obtain the optimal checkpoint frequency function in Eq.(11)

$$n_F(t) = \sqrt{\frac{k}{O_F}} \cdot \sqrt{\frac{f(t)}{1 - F(t)}}, \qquad k \in (0, 1) \tag{11}$$

It is worth mentioning that the probability density function (PDF) and the cumulative distribution function (CDF) can be the joint PDF and joint CDF where each corresponding marginal is the failure distribution of each node in an HPC system.

2.2 Estimation of the Re-computing-time Coefficient k

In Figure 4, T_{Re} is the re-computing time of the application recovered after the failure. It is the time interval between the last checkpoint and the failure, which is a random variable depending on the time when the failure occurs from the checkpoint placement.

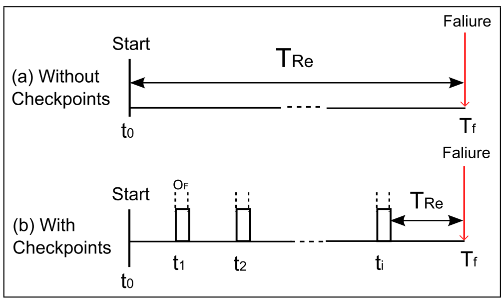

Figure 4: T_{Re} (a) without checkpoint, and (b) with checkpoint

In an application without checkpoints (Figure 4(a)), if a failure occurs at time T_f, then $T_{Re} = T_f - t_0$. With checkpoints (Figure 4(b)), it is obvious that T_{Re} is a random variable which depends on the time the failure occurs. Therefore, if we know the distribution of the time between failures, then T_{Re} can be estimated.

Definition 2. The re-computing time coefficient k is the ratio between the re-computing time and the checkpoint interval in which a failure occurs. As such,

$$k = \frac{T_{Re}}{t_{i+1} - t_i} = \frac{T_f - t_i}{t_{i+1} - t_i}$$

To estimate k, we first obtain the expected re-computing time for each checkpoint interval.

Definition 3. Excess life is a random variable, $S \geq 0$, which denotes system survival until time $t + S$ given that it survives until time t. We denote the CDF, the PDF, and the expected value of the excess life S as

$$\begin{aligned} &F(t+s|t) = P\left(T_f < t + S | T > t\right), \\ &f(t+s|t) = \tfrac{dF(t+s|t)}{ds}, \\ &E[S] = \textstyle\int_0^\infty s f(t+s|t)\, ds. \end{aligned} \tag{12}$$

In our checkpoint model, each checkpoint time t_i is the time that we expect a failure to occur. The re-computing time during the interval (t_i, t_{i+1}), T_{Rei} is a random variable such that its value is in the interval $(0, t_{i+1} - t_i)$. According to the excess life definition, the expected value of the re-computing time can be calculated as

$$E[T_{Rei}] = \int_0^{t_{i+1}-t_i} s f(t_i + s|t_i)\, ds \Big/ \int_0^{t_{i+1}-t_i} f(t_i + s\,|\,t_i)\, ds. \tag{13}$$

Therefore, for the expected k of the i^{th} checkpoint interval, $\bar{k}_i$, we obtain

$$\bar{k}_i = E[T_{Rei}] \big/ (t_{i+1} - t_i). \tag{14}$$

Hence, the expected k, $\bar{k}$, can be express as

$$\bar{k} = \sum_{i=1}^{N} P_i \bar{k}_i \Big/ \sum_{i=1}^{N} P_i, \tag{15}$$

where $P_i = P\left(t_i < T_f < t_{i+1} | T_f > t_i\right)$ and N is the number of the checkpoints.
To estimate k iteratively, we assume an initial value $\hat{k}$ between 0 and 1. We then calculate the corresponding checkpoint sequence, $t_1, t_2, ..., t_N$, from Eq.(11). Next, we calculate $\bar{k}$ corresponding to the checkpoint sequence using Eqs. (13)(14)(15). We repeat the above procedure by varying $\hat{k}$ until we obtain a $\bar{k}$ value that is equal to $\hat{k}$.

<u>Algorithm to estimate k</u>
STEP 1: Assume $\hat{k} = a$, $a \in (0, 1)$ and set $t_0 = 0$

STEP 2: Calculate the checkpoint sequence $t_1, t_2, ..., t_N$ corresponding to $\hat{k}$ from Step 1.

STEP 3: Calculate $\bar{k}$ from Eqs. (13)(14)(15) using the sequence in Step 2.

STEP 4: IF $\hat{k} = \bar{k}$, THEN set $k = \hat{k} = \bar{k}$ DONE
ELSE repeat Step 1.

2.3 Full Checkpoint Model Evaluation

Full Checkpoint Model for the Exponential Distribution

By substituting $f(t) = \lambda e^{-\lambda t}$, and $1 - F(t) = e^{-\lambda t}$ in Eq.(11), the checkpoint frequency function for the exponential distribution with the failure rate λ, according to Eq.(11), is given by

$$n_F(t) = \sqrt{\frac{k}{O_F}} \cdot \sqrt{\lambda}. \tag{16}$$

By the definition of the checkpoint frequency function, for i=0, 1, 2... we have that $\int_{t_i}^{i+1} n_F(t)\, dt = 1$, (19)

$$\int_{t_i}^{i+1} \sqrt{\frac{k}{O_F}} \cdot \sqrt{\lambda}\, dt = 1, \tag{17}$$

$$t_{i+1} = \sqrt{\frac{O_F}{k}} \cdot \sqrt{\frac{1}{\lambda}} + t_i. \tag{18}$$

Using induction when$t_0 = 0$, the sequence of the optimal checkpoint placements for the exponential distribution with failure rate λ is given by

$$t_i = \sqrt{\frac{O_F}{k}} \cdot \sqrt{\frac{1}{\lambda}}, \qquad k \in (0,1) \tag{19}$$

where t_i is the i^{th} checkpoint placement.

The checkpoint interval can be obtained by calculating the formula $t_i - t_{i-1}$, where $i \in \{1, 2, ...\}$ and $t_0 = 0$. Then the checkpoint interval for the exponential distribution is expressed as $\sqrt{\frac{k}{O_F}} \cdot \sqrt{\frac{1}{\lambda}}, k \in (0,1)$. Therefore, according to the proposed model for the exponential distribution, the checkpoint interval is a constant. This reflects the fact that if failures follow the exponential distribution, the failure rate is a constant.

Estimation of the Re-computing Time Coefficient k for the Exponential Distribution

According to our re-computing time coefficient estimation in Section 2.2, let $\hat{k} = a,\ 0 < a < 1$ and let its corresponding checkpoint time sequence be $\{t_i\}_{i=0}^{N}$.

The CDF, PDF, and expected value of the excess life following an exponential distribution can be derived from Eq.(12) to give

$$F(t_i + s) = P(t_i + s|t_i) = 1 - e^{-\lambda t}, \tag{20}$$

$$f(t_i + s) = \lambda e^{-\lambda t}, \tag{21}$$

$$E[T_{Rei}] = 1 - \left(\sqrt{\frac{k}{O_F}} \sqrt{\lambda} \bigg/ 1 - e^{-\lambda \sqrt{\lambda} \sqrt{\frac{O_F}{k}}} \right) \tag{22}$$

By substituting Eq.(22) into Eq.(14), we obtain the expected k of the i^{th} checkpoint interval ($\bar{k}_i$) and for the expected $\bar{k}$ we use Eq.(15).

3 Incremental Checkpoint/Restart Model

3.1 Behavior of the Incremental Checkpoint/Restart Model

Although full checkpoint/restart mechanism helps to reduce the overall waste time of an application in the case of a failure taking place, we have to spend some time to save the application states, so-called checkpoint overhead. If the checkpoint overhead can be reduced, we may have a cheaper waste time. Incremental checkpoint mechanism was introduced to reduce the checkpoint overhead by saving the pages that have been changed instead of saving the whole process [12], [8], [13],[18] .

In the incremental checkpoint scheme in Figure 5, the first checkpoint is typically a full checkpoint. After that, the mechanism determines which pages have changed since the last checkpoint and saves only those pages and repeats this process until another full checkpoint is performed. In order to recover the application, we will load a saved state from the last full checkpoint and load the changed pages from each incremental checkpoint following the last full checkpoint. This results in more expensive recovery cost than the recovery cost of the full checkpoint mechanism. Thus, finding the number of incremental checkpoints between two consecutive full checkpoints that balances the recovery cost and the total checkpoint overhead is crucial. This is because too many incremental checkpoints will lead to unnecessary recovery cost. A challenge in achieving minimum overhead using incremental checkpointing schemes is to find a maximum number of incremental checkpoints while maintaining lower waste time than traditional checkpoint mechanism. The behavior of incremental checkpoint/restart model is illustrated in Figure 5.

The incremental checkpoint model consists of two types of checkpoints (full checkpoints and incremental checkpoints). The meaning of each parameter in the incremental checkpoint/restart model is listed in Table 2.

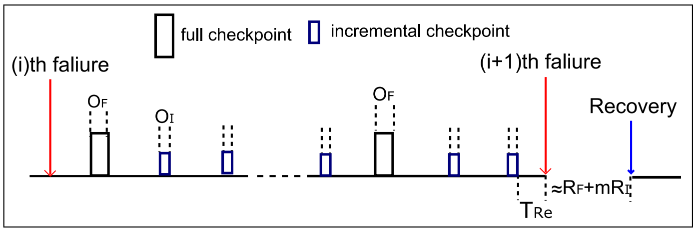

Figure 5: Behavior of Incremental checkpoint/restart model

Table 2: Parameters in Incremental Checkpoint/Restart Model.

Parameters	**Definitions**
O_F	Full Checkpoint Overhead.
O_I	Incremental Checkpoint Overhead.
T_b	Re-computing time
R_I	Recovery time per an incremental checkpoint.
R_F	Recovery time per a full checkpoint
m	Number of incremental checkpoints between two consecutive full checkpoints.
ω_i	The cycle between failure (i-1) and failure i where i = 1,2,3,...
$n_I(t)$	Checkpoint frequency function for the incremental checkpoint model

In our incremental checkpoint model, the recovery cost is decided by the number of incremental checkpoints. After m incremental checkpoints are performed, either another incremental checkpoint or a full checkpoint can be performed. A full checkpoint is chosen if the cost of performing a full checkpoint is cheaper than the recovery cost for an incremental checkpoint. This is what we call a breakeven point. The main idea is to balance a cost saving function with full and incremental checkpoint overheads and the complexity of the recovery that is introduced by the incremental model.

The incremental checkpoint model is an extension of the above full checkpoint model, so the assumptions of the full checkpoint model are applied to this incremental checkpoint model as well. However, there are additional assumptions regarding the factors in the incremental checkpoint scheme which are listed as follows:

1. The first checkpoint in an application is a full checkpoint. After an application is recovered from failure, the first checkpoint is a full checkpoint as well. After m consecutive incremental checkpoints, a full checkpoint may be performed if the overall cost reaches a breakeven point between incremental and full checkpoint. We will determine the value of m in the next section.

2. The incremental checkpoint overhead (O_I) may be viewed as an average of all incremental checkpoint overhead performed. Although, for an application, there are both small and large incremental checkpoint overheads, this assumption is reasonable because we aim to minimize the waste time caused by the incremental checkpoint mechanism of an application.

3. The recovery cost of the incremental checkpoint (R_I) and the number of incremental checkpoint between two consecutive full checkpoints m is a constant. The evaluation of m is given in Section 3.3.

In future work, we will extend the model to consider the incremental checkpoint overhead and the number of incremental checkpoints m as functions of time, in order to better represent a realistic scenario.

Definition 4. Let the sequence of discrete checkpoint placements be $0 = t_0 < t_1 < ... < t_n$, and the checkpoint frequency function for the incremental checkpoint model denoted by $n_I(t)$ is defined by $\int_a^b n_I(t)\,dt$ =the number of full and incremental checkpoints from time a to time b.

We still can imply that $\int_{t_i}^{t_{i+1}} n_I(t)\,dt = 1$. In Figure 5, the total number of checkpoints in cycle ω_i is

$$\int_0^{\omega_i} n_I(t)\,dt = N_F + N_I \tag{23}$$

where N_F is the number of full checkpoints in cycle ω_i and N_I is the number of incremental checkpoints in the same cycle ω_i.

We note that $N_I \approx mN_F$ and $N_F \approx \int_0^{\omega_i} n_I(t)\,dt$. Thus, $N_F = \frac{1}{m+1}\int_0^{\omega_i} n_I(t)\,dt$ where m is the number of incremental checkpoint between two consecutive full checkpoints.

We recall that the checkpoint procedure is a renewal process. Therefore, whenever a failure occurs, the new cycle starts. We follow the renewal reward theory to derive the optimal incremental checkpoint/restart model similarly to the full checkpoint model.

Therefore, to minimize the overall waste time of the incremental checkpoint model, it is sufficient to find the checkpoint frequency function $n_I(t)$ that minimizes only the waste time of the first cycle which consists of full checkpoint overhead, incremental checkpoint overhead, recovery time, and re-computing time in the first cycle. The waste time of the first cycle can be expressed as

$$W_1 = O_F \frac{1}{m+1}\int_0^{\omega_i} n_I(\tau)\,d\tau + O_I \int_0^{\omega_i} n_I(\tau)\,d\tau + (R_F + mR_I) + T_{Re}. \tag{24}$$

We suppose that the system can be successfully recovered from the last checkpoint, and the rollback cost T_{Re} can be estimated by $k/n_I(\omega_1), (0 < k < 1)$ as in the full checkpoint model, where $n_I(\omega_1)$is the checkpoint frequency at time ω_1, and k can be evaluated by the similar method as in the full checkpoint scheme. Therefore, we substitute T_{Re} in Eq. (25) and obtain:

$$W_1 = \left(\frac{O_F + mO_I}{m+1}\right)\int_0^{\omega_i} n_I(\tau)\,d\tau + (R_F + mR_I) + \frac{k}{n_I(\omega_1)}. \tag{25}$$

By following the stochastic renewal reward process theory, minimizing the overall waste time is equivalent to minimizing waste time in cycle ω_1. The expected waste time during a cycle in the checkpoint process $E[W_1]$ is

$$E[W_1] = \int_0^{\infty}\left[\left(\frac{O_F + mO_I}{m+1}\right)\int_0^{\omega_i} n_I(\tau)\,d\tau + (R_F + mR_I) + \frac{k}{n_I(\omega_1)}\right].f(t)\,dt \tag{26}$$

We are now looking for the solution of the overall checkpoint frequency $n_I(t)$ to minimize Eq.(26).

<u>*Solution:*</u> Let $x(t) = \int_0^t n_I(\tau)d\tau$, then $x'(t) = n_I(t)$. From Eq. (26), we obtain:

$$E[W_1] = \int_0^{\infty}\left[\frac{O_F + mO_I}{m+1}x(t) + (R_F + mR_I) + \frac{k}{x'(t)}\right]\cdot f(t)\,dt. \tag{27}$$

Let the function under the integral in right side of Eq.(27) be$\Phi(x, x', t)$. Then

$$\Phi\left(x, x', t\right) = \left[\frac{O_F + mO_I}{m+1}x(t) + (R_F + mR_I) + \frac{k}{x'(t)}\right] f(t). \tag{28}$$

By following the same argument as in the full checkpoint model, the checkpoint frequency function of the incremental checkpoint model can be expressed as:

$$n_I(t) = \sqrt{\frac{(m+1)k}{O_F + mO_I}}\sqrt{\frac{f(t)}{1 - F(t)}},\ k \in (0,1). \tag{29}$$

Practically, the incremental checkpoint mechanism is an extension of the full (regular) checkpoint mechanism in the sense that incremental checkpoints are performed additionally in order to reduce the total checkpoint overhead of the full checkpoint mechanism. Alternately, we can see that the full checkpoint mechanism is the incremental checkpoint mechanism without any incremental checkpoints. According to Eq.(11) and Eq.(29), the derived models satisfy the connection between the full and incremental checkpoint mechanisms. That is, when m is equal to 0, the incremental checkpoint frequency function, Eq.(29), becomes the full checkpoint frequency function, Eq.(11).

3.2 Estimation of the Consecutive Incremental Checkpoint Number, m

We denote the number of incremental checkpoints between two consecutive full checkpoints as m. The value of depends on the next checkpoint type, either incremental or full checkpoint. As discussed earlier, the incremental checkpoint aims to reduce the checkpoint overhead. On the other hand, the recovery cost will increase as the number of subsequent incremental checkpoints (m) increases. This is because the application reconstruction phase requires information from each and every incremental checkpoint since the last full checkpoint. From the model description of the incremental checkpoint below, we assume that the first checkpoint is a full checkpoint, followed by a sequence of incremental checkpoints. Moreover, we will perform m incremental checkpoints after a full checkpoint if the expected waste time of having $m+1$ incremental checkpoint is more expensive than that of having m incremental checkpoints. We follow this idea to find m by comparing the expected waste time in two possible cases. In the first case, as shown in Figure 6(a), m continuous incremental checkpoints are followed by a full checkpoint. Alternatively, as shown in Figure 6(b), after placing m continuous incremental checkpoints, we continue to perform the $m+1^{th}$ incremental checkpoint. In each case, we consider the probability of failure. Details are discussed in what follows.

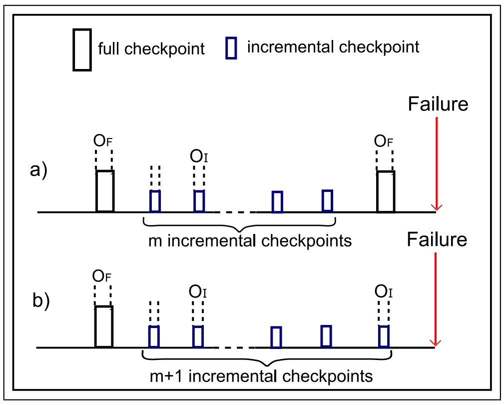

Figure 6: Sequential incremental checkpoint scenario

Case (a): After placing m continuous incremental checkpoints, a full checkpoint is performed next as shown in Figure 6(a).

Let P_I is the probability that a failure will occur after the second full checkpoint and before the next incremental checkpoint. Hence, $1-P_I$ is the probability that failure will not occur in that period.

If no failure occurs during this period, the overall cost is C_{a1}, $C_{a1}=(O_F+mO_I)+O_F$. Alternatively, if the failure occurs, the cost C_{a2} is $C_{a2}=(O_F+mO_I)+O_F+R_F$. Therefore, the expected cost is

$$C_a=(1-P_I)(2O_F+mO_I)+P_I(2O_F+mO_I+R_I). \quad (30)$$

Case (b): After reaching m consecutive incremental checkpoints, another incremental checkpoint is performed as shown in Figure 6(b). We consider that the probability of the failure events is approximately the same as in case (a), P_I.

When no failure occurs, the cost C_{b1} is $C_{b1}=(O_F+mO_I)+O_I$. Alternatively, if a failure happens, the cost C_{b2} is $C_{b2}=(O_F+mO_I)+O_I+(R_F+(m+1)R_I)$.

Therefore, the expected cost in case (b) is

$$C_b=(1-P_I)[O_F+(m+1)O_I)+P_I[O_F+(m+1)O_I+(R_F+(m+1)R_I)]. \quad (31)$$

We would like to have the number of incremental checkpoints as much as possible that yields the criteria that if another incremental checkpoint is added the expected waste time is larger than that of having another full checkpoint, and then the solution of m must be satisfied $C_b \geq C_a$. Thus, we will choose case (a) and perform a full checkpoint after m sequential incremental checkpoints.

Therefore, we obtain

$$m \geq \frac{O_F-O_I}{P_I R_I}-1. \quad (32)$$

Inequality (32) suggests us that if $m \geq \frac{O_F - O_I}{P_I R_I} - 1$, the cost in case (b) will be greater than the cost in case (a). Thus, we take m as

$$m = \left\lceil \frac{O_F - O_I}{P_I R_I} - 1 \right\rceil, \tag{33}$$

where $\lceil \cdot \rceil$ is the ceiling function.

According to Eq.(33), m is proportional to the difference between the full and the incremental checkpoint overhead and inversely proportional to the incremental recovery cost and the probability of a failure occurrence P_I. The following points need to be raised at this point. Firstly, if the incremental checkpoint overhead O_I is nearly as large as the full checkpoint overhead O_F, performing incremental checkpoints instead of full checkpoints may not reduce the total overhead. In Eq.(33), when O_I approaches to O_F, the nominator approaches 0, then the number of incremental checkpoints m is small. Secondly, all incremental checkpoints following the last full checkpoints must be loaded after a failure occurs, causing extra cost in the application recovery period. Thus, if the incremental checkpoint recovery cost is expensive, then the number of incremental checkpoints should be small in order to maintain the low recovery cost. Thirdly, a full checkpoint should be performed when a chance of a failure occurrence is high because, when a failure happens, there are few incremental checkpoints to be loaded. Therefore, if the failure probability P_I is high, the number of incremental checkpoints m is small as in Eq.(33). Lastly, the number of incremental checkpoints m does not depend on the full checkpoint recovery cost because there is only one full checkpoint loaded during the application recovery time.

3.3 Incremental checkpoint Model Evaluation

We obtained the general solution for our incremental checkpoint model. Eq.(29) gives a checkpoint frequency function which is derived from a probability distribution function of the system time between failures (TBF). For the purpose of the incremental checkpoint/restart study and evaluation, we validate our model results only when the system failure follows the exponential distribution. This assumption will help simplify our validation. However, we plan to use these results as a guidance to further our study with other distributions such as time-varying one for the system failures.

Incremental checkpoint Model for the Exponential Distribution

For the time between failures (TBF) that follows an exponential distribution, we substitute$f(t) = \lambda e^{-\lambda t}$, and $1 - F(t) = e^{-\lambda t}$, $t \geq 0$, $\lambda > 0$ in Eq.(34).

The optimal model for an exponential Distribution can be written as

$$n_I(t) = \sqrt{\frac{(m+1)k}{O_F + mO_I}}\sqrt{\lambda}. \tag{34}$$

We can find the i^{th} checkpoint placement. For $i = 0, 1, 2, \ldots$ we have that:

$$\int_{t_i}^{t_{i+1}} \sqrt{\frac{(m+1)k}{O_F + mO_I}}\sqrt{\lambda}\, dt = 1. \tag{35}$$

Solving Eq.(35), we have that:

$$t_{i+1} = \sqrt{\frac{O_F + mO_I}{(m+1)k}}\sqrt{\lambda} + t_i. \tag{36}$$

Using induction and taking $t_0 = 0$, the sequence of the optimal checkpoint placements for the exponential distribution with failure rate λ is given by

$$t_i = i\sqrt{\frac{(m+1)k}{O_F + mO_I}}\sqrt{\frac{1}{\lambda}}, \ \ k \in (0, 1), \tag{37}$$

where t_i is the i^{th} checkpoint placement either full checkpoint or incremental checkpoint. In Eq.(37), the number of incremental checkpoints can be obtained by Eq.(33), and we can obtain the failure probability P_I analytically. Please note that the checkpoint interval $(t_{i+1}-t_i)$ is a constant equal to $\sqrt{\frac{(m+1)k}{O_F+mO_I}}\sqrt{\frac{1}{\lambda}}$. From Eq.(33), the probability P_I of failure during the $(t_{i+1}-t_i)$ interval is

$$P_I = P\left(T_f < t_{i+1} | T_f > t_i\right) = \frac{F\left(t_{i+1}\right) - F\left(t_i\right)}{1 - F\left(t_i\right)} \tag{38}$$

For the exponential distribution, the CDF is $F(t) = 1 - e^{-\lambda t}$, and we have

$$P_I = \frac{\left(1 - e^{-\lambda t_{i+1}}\right) - \left(1 - e^{-\lambda t_i}\right)}{1 - \left(1 - e^{-\lambda t_i}\right)} \tag{39}$$

Since the checkpoint interval is constant and $t_{i+1} - t_i = t_1 - t_0 = t_1$, then we have

$$P_I = 1 - e^{-\lambda t_1}. \tag{40}$$

In practice, we have to find k (the re-computing time coefficient) and m at the same time.

Algorithm to find k and m:

Step 1: Initialize O_F, O_I, R_I and λ. Let $\hat{k} = 0.5$ and $t_0 = 0$.

//Find m corresponding to $\hat{k}$.

Step 2: Let $\hat{m} = 1$.
Step 3: Calculate t_1 from Eq. (35).
Step 4: Calculate P_I by Eq. (38).
Step 5: IF $\hat{m} < \frac{O_F - O_I}{P_I R_I} - 1$,
THEN $\hat{m} = \hat{m} + 1$, and go to Step 2.
ELSE go to Step 6.
Step 6: Set $m = \hat{m} - 1$

//Finished finding m

Step 7: Calculate the checkpoint sequence $t_1, t_2, ..., t_N$ corresponding to $\hat{k}$ and m from Eq. (35)
Step 8: Calculate $\bar{k}$ from Eqs. (11)(12)(13) using the sequence in Step 7.
Step 9: IF $\hat{k} = \bar{k}$,
THEN Set $k = \hat{k}$ DONE
ELSE Set $\hat{k} = \bar{k}$, and go to Step 1.

4 Comparisons between the Full Checkpoint Model and the Incremental Checkpoint Model

In this section, we assume that the waste time of the incremental checkpoint model would be less than that of the full checkpoint model. As we discussed before, the incremental checkpoint scheme aims to reduce the total checkpoint overhead. In contrast, it introduces more expensive recovery cost than the full checkpoint mechanism. Therefore, in order to provide evidences to the assumption, the comparisons between the waste times of both models are performed based on the actual failure data of White and Frost HPC systems.

White and Frost were IBM supercomputers at Lawrence Livermore National Laboratory. White consisted of 512 nodes with 16 processors per node and 8192 processors in total, and Frost consisted of 68 nodes with 16 processors per node and 1088 processors in total. Although White and Frost systems had retired already at July 26, 2006 and June 30, 2005, respectively, we choose both systems to analyze because we have the failure timestamps of both systems over the period of four years from 2000 to 2004.

Before we run the simulations, we process both failure data sets (White and Frost) as the following. First, we use the time window of one month to break the failure time stamps, and we then have 52 sets of failure times of White system and 50 sets of failure times of Frost system. Second, for each data set, we calculate the times between failures (TBFs) and the mean time between failures (MTBF). Next, the Kolmogorov-Smirnov test is used to test the null hypothesis that the data sets follow the exponential distribution with the corresponding MTBF with the significance level of 0.1. After the test, there are 33 sets of TBFs of White and 42 sets of TBFs of Frost that follow the exponential distribution. These are the samples that we will use in the simulations for both systems. Furthermore, the MTBF of the White samples is around 23 hours, and the MTBF of the Frost samples is around 70 hours.

An objective of the simulations is to study the ratio between the waste time and the application completion time, denoted as RWC. The application completion time is the time from the beginning of the application computation to the completion including the checkpoint overhead, recovery time, and re-computing time. RWC can be used as a metric to evaluate the efficiency of the models. For example, if RWC value approaches 0, most of application execution time is used to compute the application, which indicates that the performances of the proposed models are likely to be good. Otherwise, most of application execution time is the waste time. However, there is no standard or threshold to indicate the goodness of a checkpoint model yet. To simulate the waste time of both models, for each TBF data set, the following procedure is applied. We determine the checkpoint sequences for the full and incremental checkpoint models, and then, for each sequence of TBFs, we compute the waste times for different completion time values, as the range of 0 to 30 days with the increment of 1 day. Next we calculate RWC of each completion time value and find the average of RWC over the completion time.

Four experiments are conducted with different values of full checkpoint overhead (0.5, 2, 10 and 30 minutes). For each experiment, we calculate the average of RWC for the full checkpoint model and the incremental checkpoint model with 3 different values of incremental checkpoint overheads as 10%, 50%, and 90% of the full checkpoint overhead. Therefore, we have 16 values of RWC in total for White and Frost systems as shown in Figure 7, Figure 8, respectively.

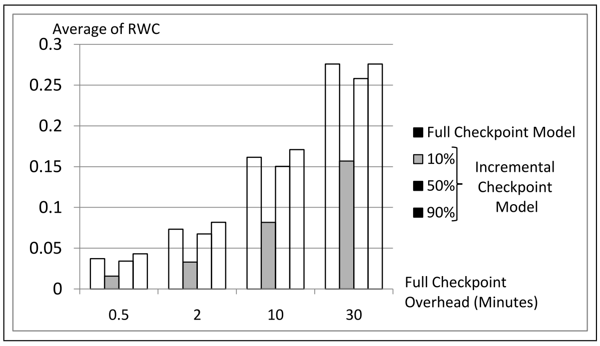

Figure 7: White Average of *RWCs* of the full checkpoint model and the incremental checkpoint model with different values of full checkpoint overhead of 0.5, 2, 10, and 30 minutes and different values of incremental checkpoint overhead of 10%, 50%, and 90% of the full checkpoint overhead values.

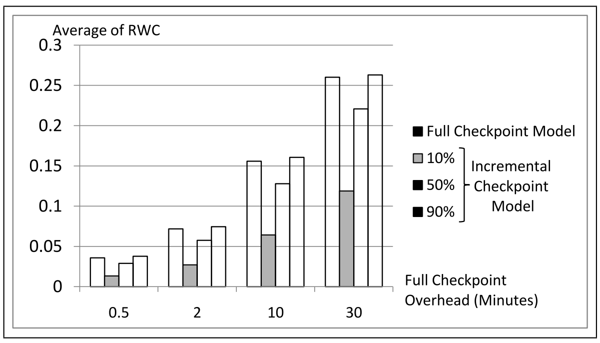

Figure 8: Frost Average of RWCs of the full checkpoint model and the incremental checkpoint model with different values of full checkpoint overhead of 0.5, 2, 10, and 30 minutes and different values of incremental checkpoint overhead of 10%, 50%, and 90% of the full checkpoint overhead values.

According to Figure 7 and Figure 8, in every case of full checkpoint overheads, we notice that the proportions of the RWCs of the incremental checkpoint model are not implied by the ratio between the incremental checkpoint overhead and the full checkpoint overhead. For example, when the incremental checkpoint overhead is 10% of the full checkpoint overhead, the averages of RWCs of the incremental checkpoint model is approximately half of the averages of RWCs of the full checkpoint model. In practice, we expect that the waste time of the incremental checkpoint scheme should be less than the full checkpoint scheme, but the graphs show that, while the incremental checkpoint overhead is 90% of the full checkpoint overhead, the average of RWCs of the incremental checkpoint scheme is slightly greater than that of the full checkpoint scheme. Moreover, the behaviors of the RWC in White and Frost system are very similar although the MTBFs of both systems are notably different. We may imply that our model is able to give similar results in other systems.

Additionally, the full checkpoint model for the Weibul distribution has been compared with the Risk-Based model [10] in [21]. In the Risk-Based model, a checkpoint will be performed if the waste time when the checkpoint is performed is less than the waste time when the checkpoint is not performed. In [10], there are three other models, but the Risk-Based model was the only model chosen for comparison because it is the best one among all the models in [10]. According to [21], with different values of checkpoint overhead, the full checkpoint model produced less waste time than the Risk-Based model, except for the case when the full checkpoint overhead is equal to 1 hour. In this case, the waste times of both models were very similar.

5 Conclusions

In this paper, we have presented near optimal checkpoint/restart models in full and incremental checkpoint schemes in a large-scale HPC environment. In these models, the time sequence of checkpoint placements was derived using the theory of a stochastic renewal reward process. The models are general and can be applied to any distribution of time between failures. However, the given example is for the case of the exponential distribution. The re-computing time which directly relates to the failure time, is an important factor in a checkpoint/restart model. Instead of using the re-computing time, we introduced the re-computing time coefficient (k), its estimation approach, and an algorithm to estimate k. For the incremental checkpoint model, there is another significant factor which is the number of incremental checkpoints between consecutive two full checkpoints (m). The derived m yields the event that the expected waste time of performing a full checkpoint after m incremental checkpoints is less than that of performing the $(m+1)^{th}$ incremental checkpoint. The proposed algorithm does not provide only the evaluation of m but also the re-computing time coefficient. For the model analysis part, the failure data of White and Frost, the supercomputing system owned by LLNL were used to simulate the waste time of both proposed models. The comparisons between both models are provided. In most cases, the waste times of the incremental checkpoint model are less than those of the full checkpoint model, especially when the incremental checkpoint overhead is much less than the full checkpoint overhead. Furthermore, the proportion of the waste times of the incremental and full checkpoint models seems to not relate to the ratio of the incremental and full checkpoint overheads. Lastly, the results of White and Frost systems are very similar. This may indicate that the proposed models are able to give similar results for other systems.

6 Future Work

In the near future, we will extend the incremental checkpoint model for the case where the number of incremental checkpoints between two consecutive full checkpoints is not a constant. We expect that the extended model will give less waste time than the proposed one. Moreover, we will improve the method to evaluate the number of incremental checkpoints between two consecutive full checkpoints to yield optimality. In addition, we will work on improving the models. For example, in some applications, there are many communications between nodes. If one performs a checkpoint while there is a large amount of communications going on, the checkpoint overhead will be expensive. Therefore, the communication or I/O transfer rate may be another factor to consider when performing a checkpoint.

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3D Virtual Spaces Supporting Engineering Learning Activities

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Abstract: Virtual environments constitute the support platform for various teaching and learning activities. Instead of a local application for this purpose, this paper explores the effects of using distributed virtual reality environments in the educational process. The architecture of the presented system is based on the recently developed web-based technology called AJAX (Asynchronous Javascript And XML), implemented on a Linux operating system configured to run Apache with PHP and MySQL support; i.e., LAMP architecture, which contributes to the portability and ease of installation of the application. The platform is designed to support the integration of lesson modules such as the EngView environment which is discussed in more detail in this contribution. Pedagogical, technical, and implementation-related aspects are presented in conjunction with the virtual environment used in the engineering training curriculum. Statistical information resulted from the training shows a significant increase in task completion time when the virtual setup is used.
Keywords: Virtual environment, Learning, Teaching, Motivation, Virtual training.

Knowledge acquisition has shifted from an individual to a collective activity. There is a migration of the learning process from one individual to a group of individuals as knowledge becomes a collective activity enhanced by the phenomena of social interaction. The complexity of the information and the way we interact with it makes us active parts in the educational environment. Searching, discovering, and testing are the most frequent human activities in such situations. When an interpretive level of comprehension is reached, these activities are mature enough to trigger creational thinking, and constitute the beginning of the applied level of understanding. As complements to learning, virtual training gives constructive feedback to learners by providing them with a hands-on approach to the studied subject.

In the following sections, we emphasize the potential of distributed virtual environments to improve the learning process. To prove the point, we try to answer one question: "*What do the 3D virtual spaces bring into the learning processes in order to make them effective and evolutionary?*"

1 Introduction

A three-dimensional (3D) virtual space is a computer-generated space that is perceived by us via pure virtual reality (VR) technologies and/or mixed reality (MR) technologies [1]. This perception can only be obtained through placing the user in the space, from the user's interaction with the space. Furthermore, this space is not passive since the users interact with each other and/or with other virtual entities, by the means of virtual agents or avatars. Virtual objects are subjects in the users' direct or indirect interactions and may enhance collaboration between users. Users' multimodal communication is realized through exchanging typed or verbal messages, gestures, and facial expressions.

In other words, the virtual space must be constructed, first of all, considering the user's cognitive and empirical attributes. This means that when we create virtual space models, the base criterion should be the accuracy of the human representation of reality which may not necessarily correspond with reality. To this end, the human experience is first constructed by situating the user in the virtual context, then tested through the user's direct interaction with the environment, and later reconsidered, in a recursive process.

How efficient and effective is such experience? A possible answer may be given by evaluating the user experience in the frameworks proposed by Burdea [2] and Zelter [3]. We do not discuss the imagination aspect of the user experience but leave it private to the user. It may surprise the reader, but we are not trying to obtain an accurate sensorial rendering of the virtual space in order to immerse the user in the environment. Instead, by high quality immersion inside this virtual space we mean intense user interactivity with objects or other users within the virtual space.

The efficiency and the effectiveness of such experiences are considered acceptable if the user is able to apply the knowledge and skills obtained in the virtual space in similar real-space conditions; i.e., if both the gained knowledge and skills are reusable.

Applying such virtual spaces in learning and teaching activities provides the conditions for transforming the sometimes passive actors (i.e., students and teachers) into involved, very active actors [4]. With the support of new technologies, we hope to infuse them the sensation that they represent active parts of the learning/teaching process [5].

Our goal is to catalyze the creative state-of-mind and self-confidence at an individual level as premises of collaboration among individuals, with personal perspective as the basis for the learning communities. These communities provide the necessary conditions for transforming the users' interactions, expressed through direct communication and cooperation with other individuals, into long-term social interactions.

Many educational virtual environments such as "virtual theatre" and "virtual classroom" use various metaphors to facilitate the trainee in learning on an abstract (e.g., math, physics, electronics, and other [6, 7, 8, 9]) or concrete (e.g., gesture or behavior in certain situations [10, 11]) level. Few environments take into consideration the trainee's motivation to learn. Driven by this observation, our goal is to obtain a solution designed to serve as a motivational feedback to its users.

Virtual theatre or narrative-based metaphors have one major advantage as compared to other metaphors; i.e., they challenge and encourage the user to verbalize/render his/her experience in a situational context. Such an environment is highly evolutional since every actor comes with his/her own personal experience in a similar situation; this way knowledge is collectively and continuously modeled to better express the social point of view. The more we express the knowledge, the better the result becomes. Multimodal environments that combine haptic feedback with 3D visualization and sound rendering [12] prove to be very efficient learning tools, especially for understanding abstract concepts.

As students gradually gain confidence in the team they belong to, they become autonomous and willing to acquire new knowledge; thus, they change from being dependent on the team to being independent, and the relationships among individuals become dynamic and friendly. In particular, team-based environments are suitable for interdisciplinary teams. For example, the EngView system about which we discuss in this paper was developed by a mixed team of computer scientists, engineers, and managers, as well as a group of enthusiastic students. Engaging such a team, we have attained our main pedagogical objective that is to assure a rapid and successful integration in the professional context for our students. However, some difficulties rise due to factors such as the different levels of knowledge acquired by students during their studies, the student's level of interest in the information presented and the student's motivation to learn.

Learning speed varies from person to person. Often, theory is easier to grasp than to translate into practice. Or vice-versa, practical skills are quickly acquired, even without any basic understanding of the theory. Despite these difficulties, students need to achieve good theoretical and practical skills.

At the theoretical knowledge level, the widely used method of multiple choice examinations can be computer-graded or easily marked with a template. However this method does not provide any insight into the trainee's work methods and adaptability. A much better choice is a written examination. On the other hand, practical examinations are somewhat more probing; however, the trend is to have the candidate demonstrate his/her skills in a simple application where the results can be easily and uniformly graded [13].

Because paradigms such as VR and multimodal environments facilitate learning through the construction of concepts relying on the intuition that arises from direct user experience in the virtual environment [14], we decided to complement our teaching/learning process by using these technologies. We do not eliminate multiple choice examinations, but we consider that communication and interaction within a collaborative virtual environment may represent essential motivational dimensions to the trainee. Therefore, we consider interaction and communication as being the most important requirements of VR-based training technologies.

Another important aspect is the reduced accessibility of the real training setups for a group of trainees. By means of switching between training sessions in real environment and virtual replicas, the trainee is able to obtain the confirmation of his/her practical results obtained in the virtual environment. Thus, we do not eliminate traditional assessment, but we let the students exercise longer within a virtual setup, without any physical risks and at potentially lower costs. When students reach a certain level of "virtual expertise", they are allowed to prove this expertise in a real environment.

2 EngView - a training tool for engineers

To demonstrate the effectiveness of the educational concepts mentioned above, we implemented a training environment for engineers, called EngView [15], that is a supplementary tool in the training process in the domain of non-destructive testing (NDT), as detailed in the next section.

Because the presented training environment addresses mature users, motivation may not necessarily come from the environment itself, but from the user's desire to succeed in his/her integration within a professional context. In such a context, social interactions frequently appear in team setups and trigger individual development on both theoretical and practical levels. Due to frequent switching between experimentation and theory, it is not surprising that discovery, creation, and innovation are expected side-effects in engineering learning contexts.

2.1 NDT principles

The most used formats in the NDT training process are the A-scan, B-scan, and C-scan presentations. These provide different ways of visualizing and evaluating the inspected material region. For our purposes, we have chosen to visualize only the C-scan method.

The high-frequency ultrasonic C-scan presentation provides the planar view, depth location, and size of the defects inside the probe; this makes C-scan a valuable tool to monitor the precise location of the defects between certain layers (see figure 1). The plane of the image is parallel to the scan pattern of the transducer. C-scan presentations are produced with an automated data acquisition system, such as a computer controlled immersion scanning system.

The C-scan method is based on the transmission of a very-high-frequency signal (up to 50 MHz) directed to the sample by the transducer. The sample and the transducer are submerged in a coupling medium (water in our case). The initial signal is partially reflected back to the transducer by the interface's grains, defects and porosities, or by other substantial differences in acoustic impedance in the sample and the signal of the transducer. If not fully reflected, the signal continues through the sample. In other words, between the initial pulse and the back-wall peaks there is an additional peak caused by the sound wave going from the water into the test material. This additional peak is called the "*front wall peak*". The ultrasonic tester can be adjusted to ignore the initial-pulse peak, so the first peak it will show will be the front-wall peak.

Some energy is lost when the ultrasound waves hit the test material, so the front-wall peak is slightly lower than the peak of the initial pulse. In return, the peak amplitudes and the time-of-flight of each returning signal are stored in a computer data file and processed offline to produce maps of the scanned area for the sample placed at a particular depth.

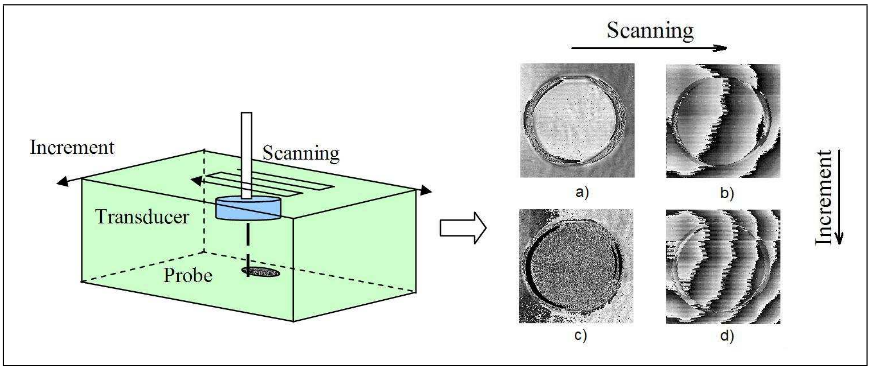


Figure 1: C-scan principle and samples of scanning

Figure 1 shows four ultrasonic C-scan images of a silicon solar plate (solar cell). All images were produced using a pulse-echo technique with the transducer scanning from above the sample in an immersion scanning system. For the C-scan image in figures 1.a and 1.c, the gate was set up to capture the amplitude of the sound reflecting from the head surface of the silicon plate. Light areas in the images indicate the regions that reflected a greater amount of energy back to the transducer. In the C-scan image in figures 1.b and 1.d, the gate was moved to record the intensity of the sound reflecting from the back surface of the plate. The details on the back surface are clearly visible, but the front surface features are also visible since the sound energy is affected by these features as it travels through the head surface of the silicon plate.

2.2 Related work

Because of the complexity of the real NDT setups, training of experts in nondestructive testing should take place in specially equipped laboratories. The cost of such a training configuration is rather great. This makes its implementation in academic laboratories difficult and, even so, the accessibility of students to the installation is reduced [16]. It also explains the small number of NDT training systems.

The Virtual Nondestructive Evaluation (NVDE) system proposed in [17] offers a full computer-based replica of a real NDT examination setup. Using NVDE, the user is able to generate the testing scenario, as trainer, to practice with the virtual setup and to perform assessment sessions to determine the performance level reached by the trainees.

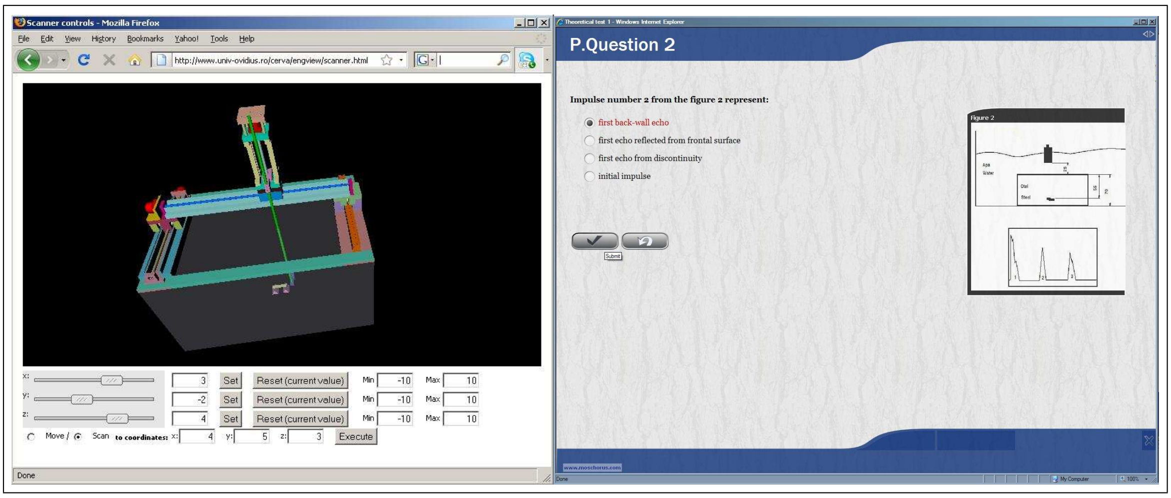
The CIVA software developed by CEA permits the visualization, optimization, and prediction of the performances of several testing techniques. Great effort is made in order to optimize the computing time so that the 3D models that are tested can be used in parametric studies, despite the potentially complex configurations. Moreover, CIVA can simulate the ultrasound wave propagation and highlight the defects inside the 3D models [18].

2.3 The virtual environment

In order to solve the problem of time limitation and lack of accessibility for more than one user that the real configuration presents, a virtual implementation of the scanner was developed. All functionalities of the real NDT installation were made accessible through EngView's 3D-immersive simulation software (see figure 2.a). This feature allows any user to practice the scanning procedure without any repercussions in case of faulty maneuvers.

This method offers a superior overview and understanding of the device and its mechanism of functioning. More precisely, the user is able to change the viewpoint inside the simulated environment (front/back, left/right, and up/down) and to navigate inside the virtual scanning device for a better view-point. These features allow the user to visualize the surface of the virtual scanned object during the simulation. The user can also move the three crane-like components of the virtual scanning device to virtually scan the simulated 3D probe.

The EngView setup was used during the second semester of 2007 in training sessions by engineering and physics senior students, organized in eight groups, each containing 25 students.



a) b)

Figure 2: EngView : a) practical session, b) theoretical assessment session

The NDT curriculum requires one practical evaluation on the basis of six laboratory hours. As mentioned before, the NDT makes no exception in both theoretical and practical evaluation. To this end, the virtual environment contains pedagogical resources that provide users with access to theoretical background and evaluation as well as to practical sessions. Students can reproduce different types of realistic experiments using the EngView system by preparing the sample, changing the type of transducer, setting the parameters of the moving engines to establish the type of scanning procedure, and to make comparative studies. The students that work on the client machines in the EngView system are able to perform the same kind of analysis as in a real system.

The EngView system can be used either independently - not coupled to the real system - by installing it on a computer, or directly connected to the scanning device. The former option gives the advantage of supporting several students to train simultaneously using their home Internet-enabled computer. Through the latter option the device is actively controlled, serving as a safe and easy way to perform experiments when accurate data is required.

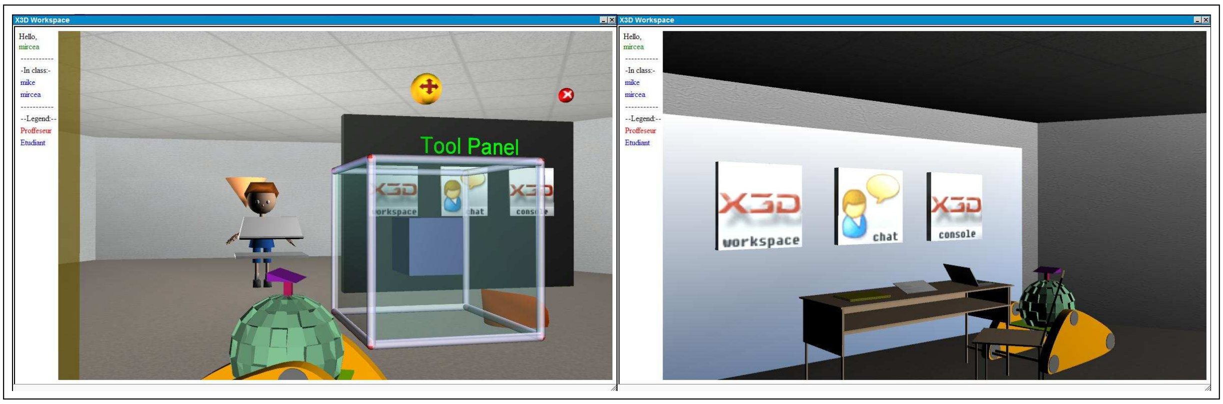
An assessment was organized on the basis of a multiple choice test containing ten pure theoretical and seven practical questions (see figure 2.b) to evaluate the knowledge acquired by the students. The time limit was 30 minutes to answer all questions. The practical evaluation had three steps: the experiment setup/calibration; the experiment itself; and the interpretation of the results. In the real configuration, about 30 minutes are necessary for the experiment per student, without any error recovery, so there is no possibility to try it twice during the exam. In this situation, it often occurs that the student uses the real NDT setup for the first time.

2.4 Emulaction - a platform for distributing learning/training activities

Although the solution described above provides the users with a more efficient learning environment, it does not support more users working together at the same time. To overcome this deficiency, we developed a context in which the simulations can take place.

This context is constituted by a virtual classroom that holds the fully functional 3D representations of each element from the real educational scenario. Organizing the learners in teams in the context offered by the "virtual classroom" metaphor helps to reduce most of the discrepancies between the individual knowledge levels increases communication and competition (in this order).

Competition becomes cooperation and aids the level of motivation. Hence, the complexity that may arise even in the most "simple" subjects is a non-declared motivational factor when introduced gradually. If the students' needs are satisfied and their expectations are met, they will strive to develop their professional competences. Indirectly, students contribute to the development of the learning context (see figure 3).



a) b)

Figure 3: Shared training environment (EMULACTION project): a) Users sharing a task, b) Virtual office containing theoretical material and assesment tools

Because the students share the real environment, we want them to share a similar virtual environment also. Students naturally start to form small work teams in the virtual setup, based on the real environment configuration. Later, these teams may evolve based on the complementary knowledge that the team members possess, in order to assure a higher level of team performance.

Shared experiences provide different, perhaps even complementary perspectives to the lesson, depending on each individual.

Combining specific tasks in a distributed platform enables the users to collaborate and focus on the same target, share knowledge and impressions. Working in teams can bring great advantages to the learning experience, as users can communicate and coordinate each other's actions in real time, while conducting the experiments.

Figure 4: EngView-based shared training session

Figure 4 shows an example of such a context, where the students that have passed the theoretical assessment have access to the virtual replica of the NDT scanning installation. Here they may test different scanning parameters and different probe materials while visualizing the same EngView environment. A virtual laptop gradually displays the scanned probe and can receive commands to either start or stop the scan. The scanning device is a fully functional replica of the real equipment, and the cranes from the standard version of EngView have been replaced by virtual disks that can be rotated to achieve the desired position of the start and end positions. The visual feedback is coherent with the used scanning parameters and may give hints to the trainee concerning the task currently in progress.

3 Implementation-related aspects

Our educational virtual environments are currently based on the assumption that knowledge and skills acquired in a VR-based environment will be transferred to the real world. The effectiveness of such an environment depends on the user's capability to apply the knowledge and/or the skills acquired to its real world counterpart.

The current learning materials are implemented using the Moodle [19] platform for the text and multimedia resources (DOC, PDF, PPT, AVI, or JPEG files) as well as 3D virtual environments.

Concerning textual and multimedia support, we explored the Moodle facilities to align the pedagogical context with the Sharable Content Object Reference Model norms [20]. Moreover, we manage the users' access to the corresponding course materials according to their curricula and the course materials. Therefore, the tutors have the ability to create, modify, and publish educational materials, such as courses, seminars, homeworks, project subjects, tests, and so on. Furthermore, using such a system, the administrator is able to manage the courses, the users, the groups of students, and the students enrolling in each course.

Our 3D environments are developed using VRML [21] and/or ARéVi API [22]. The ARéVi API is open-source, C++ and OpenGL based, and adaptive to different configurations, ranging from desktops to 3D stereoscopic immersion systems. To put all together, we use a reactive agent-based architecture [23]. This architecture assures the user's immersion and evolution within the virtual space.

To ensure the distributed activities, we have adopted the Linux, Apache [24], MySQL [25], and PHP [26] based solution. Because our educational environment is mostly 3D-oriented, we chose to build it based on the AJAX/AJAX3D technology [27, 28] and X3D/VRML language [29, 21]. AJAX provides optimal update speed between the client and the server by simulating a direct connection, while X3D has the advantage of having an accessible structure that can be controlled with the JavaScript engine through a browser plug-in called FluxPlayer [30]. FluxPlayer is easily installable on Windows (XP and Vista) operating systems for Firefox [31] and Internet Explorer browsers. The scene access interface (SAI) is achievable also through Java, but in this case we considered that having an applet to control the environment was unnecessary. This approach is still at the beginning as more and more game-like browser-based applications spread over the internet. This launch is facilitated by the increase in processing power of the personal computers, and by the ever-evolving internet browsers that are able to faster process web content. To this end, this architecture can be considered modern and unique in the context of educational purposes.

PHP and MySQL are in charge of the user account and database management. The system currently supports two account types: student and teacher, each enabling users to perform certain actions depending on their status. Apart from proving a high level of performance, the system is easy to install on any operating system that supports PHP and MySQL. Although the update speed is not real-time due to the impossibility of establishing a direct connection with the server through this architecture, this was not a factor of decision because the main objective of this application is only to provide users with a functional collaborative environment in which they can practice.

Assuming a high number of users connected to the system simultaneously, the application was optimized to cache new events to prevent unnecessary communication with the server that would cause it to slow down. Updates are transmitted using the XML format for better information structuring. XML not only brings ease in the use of the received data, but also makes the system adaptable to changes brought to its structure. Each client of the application requests updates from the server at customizable time intervals, depending on the connection speed.

The virtual classrooms also offer users tools to communicate with each other and submit results for verification, after experiments have been completed. Among these tools are the button toolbar, books and files, which are also viewable by all participants when activated (see figures 3 and 4).

The environment is designed to be customizable by the teachers that want to hold a course in of different curricula. The teacher account type offers users the freedom to create a personalized classroom, suitable for the course that needs to be held, containing adequate tools and devices for the students to use. This way, the customized classroom is dynamically generated by the application, and becomes ready for the students to join.

4 Discussions

In order to evaluate the efficiency of the virtual setup, we gathered completion time information from students trained in the classical manner and those who benefited from the virtual practice (see figure 5).

We observed that using only the traditional training sessions is neither motivating nor time-efficient. The probability of failure because of poor practical skills and/or errors that may appear during the experiment is too high for the current curricula. On the other hand, by offering students the possibility of practicing in the virtual configuration before the real one, they became more confident in their own potential due to the chance to recover from errors and to experiment with more training situations.

In addition, the number of hours dedicated by the faculty's regulations for training and practice with the scanning device is considerably small. EngView makes seminars less expensive by using complex immersive and interactive simulations which are accessible over the internet. Moreover, it brings students closer to the practical part of their education and helps them better comprehend each learned concept.

In order to evaluate the system's impact on the user's learning/training process we have compared the assessment results obtained in classical training context with those obtained after shared 3D-setup was used (see figures 6 and 7). Table 1 contains the repartition of the users' results.

For each answer data set we determined the characteristic values as the average, the mode and the

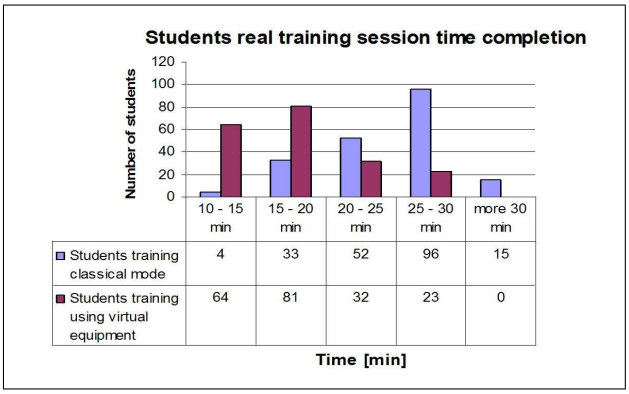


Figure 5: Comparison of training completion time in real configuration with and without virtual training sessions, respectively

variance. The first two values represent the central tendency while the variance represents the dispersion degree around the mean. The mode is the most frequent value that appears in the data set.

	Classic assesment		3D assesment	
Possible values	**Theoretical questions**	**Practical questions**	**Theoretical questions**	**Practical questions**
1	2	8	0	2
2	7	7	0	3
3	10	19	10	12
4	17	37	16	23
5	13	46	8	48
6	18	45	22	40
7	29	38	33	72
8	43	0	41	0
9	39	0	47	0
10	22	0	23	0
Total	200	200	200	200
Mean	7.025	4.965	7.39	5.6
Variance	5.134375	2.503775	3.8179	1.93
Mode	8	5	9	7

Table 1: User results in both classical and 3D training contexts and characteristic values

Based on these values and the corresponding charts (see figures 6 and 7) we can conclude that the differences indicate a significant overall improvement in the case of using the 3D setup.

In order to verify that the improvement brought by the 3D setup is indeed significant, we also applied a statistical T test for mean comparison between the two samples assuming unequal variances. The resulting P-values corresponding with theoretical assessments and practical assessments, i.e. 0.043032 and 0.000014 respectively, are smaller than 0.05; hence the difference between the means of the 2 samples is significant.

In other words, since the mean of the 3D setup is obviously higher than the classical approach, we conclude that the 3D method brings significant improvement in the training process.

We have also implemented an anonymous questionnaire that focuses on both the EngView's user interface and the environment content. We have opted for a "five-level-choice" questionnaire, with the following grades: "very poor", "poor", "acceptable", "good", and "excellent".

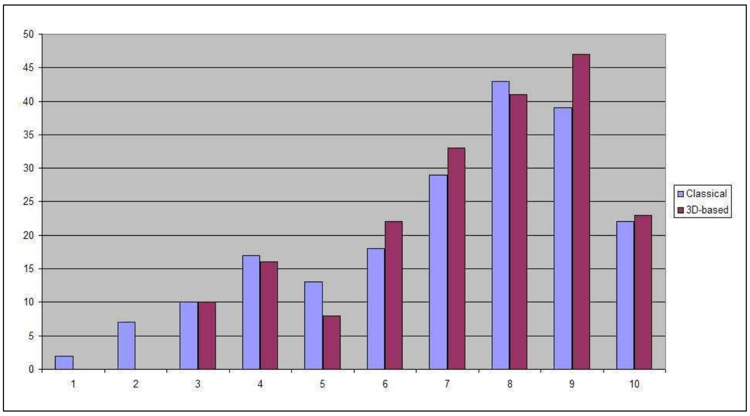


Figure 6: Results of the theoretical assessment using classical approach v.s. 3D-based one

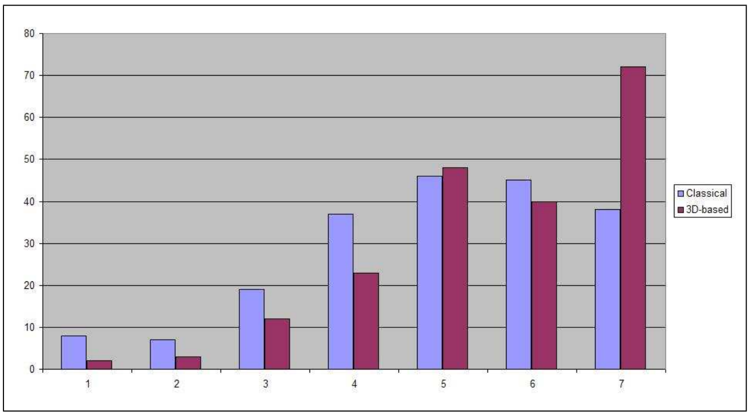


Figure 7: Results of the practical assessment using classical approach v.s. 3D-based one

Question / Answer	**very poor**	**poor**	**acceptable**	**good**	**excelent**
The interface is self-explanatory?	0%	0%	16.2%	83.5%	0.3%
The environment helps me to identify the key concept?	0%	0.28%	15.6%	83.1%	0.02%
How natural was the interaction with existing objects?	0%	0.17%	73.2%	12.97%	13.66%
How did you find the virtual NDT setup feedback?	0%	0%	1.3%	97.2%	1.5%
The reuse of the capabilities in real setup that where obtained in virtual setup	0%	0%	3%	79%	18%

Table 2: Engview evaluation questionary

As the results show (table 2), despite the specificity of the EngView environment, what we want to convey to all users of our virtual environments is self-confidence and team-oriented contexts. The virtual space has to motivate users to study the environment by direct and constructive observation of its components, without any temporal or geographical constraints. By simulating real setups into virtual spaces we encourage the users to be active situated actors in self-explanatory pedagogical contexts.

5 Conclusions and future work

As previously stated at the beginning of this contribution, the subtle goal of this work is to prove whether virtual 3D environments are able to increase the efficiency and of learning processes and their capacity of being evolutionary. First of all, people need feedback in order to comprehend the activities they perform; the lack of feedback is a major issue when dealing with the educational context because materials and equipment are often too expensive to purchase in large amounts. Having virtual simulations of the real training material lowers the costs of training, and increases the number of students that are able to be trained using them. Secondly, it was proved that collaboration increases the quality of learning, but not all virtual environments support multiple user access. Using a distributed platform that can implement various live training sessions makes possible the evolution of teams of students while training. Users receive feedback from their own actions as well as from other's, this way maximizing the intake of information. Thirdly, statistics based on the users' responses show that learning speed is greatly increased when using virtual environments in addition to classical methods. To this end, the point in adopting interactive 3D worlds in the educational context has been proven.

One of the central directions of our efforts is to use ontologies in content management and deployment. This may be useful in producing similar pedagogical situations that use different content. This may also allow us to introduce agent-oriented tutors that can evaluate the users' actions inside the 3D space.

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Fuzzy Logic Control System Stability Analysis Based on Lyapunov's Direct Method

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Abstract: A stability analysis method for nonlinear processes controlled by Takagi-Sugeno (T-S) fuzzy logic controllers (FLCs) is proposed. The stability analysis of these fuzzy logic control systems is done in terms of Lyapunov's direct method. The stability theorem presented here ensures sufficient conditions for the stability of the fuzzy logic control systems. The theorem enables the formulation of a new stability analysis algorithm that offers sufficient stability conditions for nonlinear processes controlled by a class of T-S FLCs. In addition, the paper includes an illustrative example that describes one application of this algorithm in the design of a stable fuzzy logic control system.
Keywords: fuzzy logic controller, LaSalle's invariance principle, Lyapunov function candidate.

1 Introduction

Fuzzy logic controllers have been proposed for a long time and applied successfully in many applications [1, 2, 3, 13, 14, 18]. A comprehensive work on the proof of stability of fuzzy logic control systems represents one of the challenges in fuzzy control [6, 12, 16, 17]. This paper presents a new stability analysis method for fuzzy logic control systems comprising nonlinear processes and T-S FLCs. The advantages of this method with respect to the state-of-the-art result from its specific features. First, it is different to Lyapunov's theorem in several important aspects and allows more applications. In particular, it is well-suited to controlling processes where the derivative of the Lyapunov function candidate is not negative definite. Therefore Lyapunov's direct method can cope with fuzzy control of a wide area of nonlinear dynamic systems. Second, the stability of the closed-loop system is guaranteed by the stability in each active region of the fuzzy rules. So making use of the proposed stability analysis approach determines the inserting of new fuzzy rules become very easy because just the fulfillment of one condition in the stability analysis theorem is needed.

The paper discusses the following topics. Section 2 deals with the description of the accepted class of fuzzy logic control systems. The proposed stability analysis method focused on a stability theorem based on Lyapunov's direct method and the new stability analysis algorithm that guarantees the stability of fuzzy logic control systems are presented in Section 3. Next, Section 4 offers a simple example to validate the theoretical part suggesting ways of applying the proposed algorithm. The conclusions are drawn in Section 5.

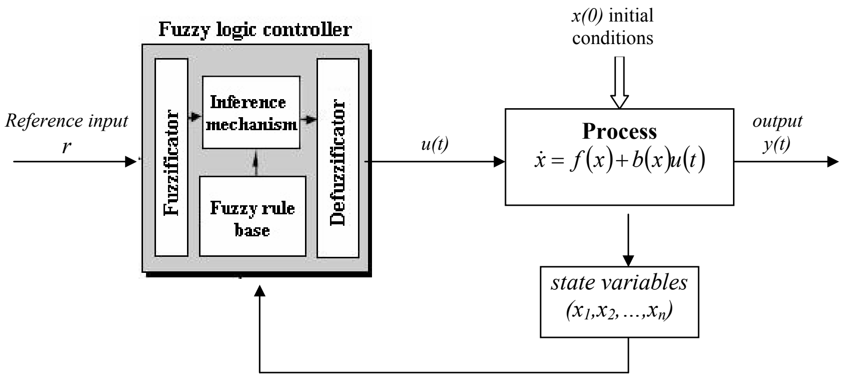

Figure 1: Fuzzy logic control system structure.

2 Fuzzy Logic Control Systems

The structure of a fuzzy logic control system consisting of a process controlled by an FLC is presented in Figure 1. Let X be the universe of discourse and consider a single-input *n-th* order nonlinear system of the following form representing the state-space equations of the controlled process:

$$\dot{x} = f(x) + b(x)u, x(t_0) = x_0, \tag{1}$$

where:

- $x \in X$, $x = [x_1, x_2, ..., x_n]^T$ is the state vector;
- $f(x) = [f_1(x), f_2(x), ..., f_n(x)]^T$, $b(x) = [b_1(x), b_2(x), ..., b_n(x)]^T$ are functions describing the dynamics of the process, $f, b : D \to R^n$ are locally Lipschitz maps from a domain $D \subset R^n$ into R^n;
- u is the control signal applied to the process input;
- the time variable, t, has been omitted to simplify the further formulation;
- $x(t_0)$ is the initial state at time t_0.

The i-th fuzzy (control) rule in the rule base of the T-S FLC base is of the form (2):

$$\begin{aligned} &Rule\ i : \text{IF } x_1 \text{ IS } X_{i,1} \text{ AND } x_2 \text{ IS } X_{i,2} \text{ AND ... AND } x_n \text{ IS } X_{i,n} \\ &\qquad \text{THEN } u = u_i(x),\ i = \overline{1,r}, r \in N^*, \end{aligned} \tag{2}$$

where r is the total number of rules, $X_{i,1}, X_{i,2}, .., X_{i,n}$ are fuzzy sets that describe the linguistics terms (LTs) of the input variables $x_k, k = \overline{1,n}$, $u = u_i(x)$ is the control signal of rule i, similar to the case of parallel distributed compensation, and the function AND is a t-norm. u_i can be a single value or a function of the state vector, x.

The structure presented in Figure 1 cam be viewed as a nonlinear state-feedback control system. However other input variables (to the FLC) can be considered as well instead of the state variables $x_k, k = \overline{1,n}$. One simple design of the fuzzy logic control system can be done in terms of parallel distributed compensation.

Each fuzzy rule generates the firing strength defined in (3):

$$\alpha_i(x) = \text{AND}(\mu_{i,1}(x_1), \mu_{i,2}(x_2) \ldots \mu_{i,n}(x_n)) \in [0, 1], \forall x \in X, i = \overline{1,r}. \tag{3}$$

It is assumed that for any $x \in X$ there exists among all rules at least one $\alpha_i \in (0,1]$, $i=\overline{1,r}$. The control signal u is a function of α_i and u_i. Applying the weighted sum defuzzification method the output of the FLC is given by

$$u = \frac{\sum\limits_{i=1}^{r} \alpha_i u_i}{\sum\limits_{i=1}^{r} \alpha_i}. \tag{4}$$

Definition 1. For any input $x_0 \in X$ if the firing strength $\alpha_i(x_0)$ corresponding to the fuzzy rule i is zero, that fuzzy rule $i, i=\overline{1,r}$, is called an inactive fuzzy rule for the input x_0; otherwise, it is called an active fuzzy rule.

It should be noted that with $x=x_0$ an inactive fuzzy rule will not affect the controller output $u(x_0)$. Hence (4) can be rewritten as follows aiming the consideration of all active fuzzy rules only:

$$u(x_0) = \frac{\sum\limits_{i=1,\alpha_i \neq 0}^{r} \alpha_i(x_0)\, u_i(x_0)}{\sum\limits_{i=1,\alpha_i \neq 0}^{r} \alpha_i(x_0)}. \tag{5}$$

Definition 2. An active region of the fuzzy rule i is defined as a set

$$X_i^A = \{x \in X \,|\, \alpha_i(x) \neq 0\}, i=\overline{1,r}. \tag{6}$$

3 Stability Analysis

The stability analysis presented in this paper is based on LaSalle's invariance principle cited and analyzed in [11]. This Section is concentrated on the formulation and proof of Theorem 1 that ensures sufficient conditions for the stability of nonlinear processes controlled by T-S FLCs.

The Lyapunov function candidate $V: R^n \to R$, $V(x) = x^T P x$ is considered. It is positive and unbounded, where $P \in R^{n\times n}$ is a positive definite matrix. Considering the state trajectories fulfilling (1) in order to obtain the closed-loop system dynamics, it results that V has continuous partial derivatives and the derivatives of V with respect to time expressed in terms of (7):

$$\begin{aligned} \dot{V}(x) &= \dot{x}^T P x + x^T P \dot{x} = (f(x) + b(x)\,u(x))^T P x + \\ &+ x^T P (f(x) + b(x) u(x)) = F(x) + B(x)\,u(x), \end{aligned} \tag{7}$$

where:

$$F(x) = f(x)^T P x + x^T P f(x), B(x) = b(x)^T P x + x^T P b(x). \tag{8}$$

The following sets are defined to be used in the stability analysis:

$$B^0 = \{x \in X \,|B(x) = 0\}, B^+ = \{x \in X \,|B(x) > 0\}, B^- = \{x \in X \,|B(x) < 0\}. \tag{9}$$

The main result is given by the following Theorem.

Theorem 3. *Let the process be described by (1) with $x=0 \in R^n$ an equilibrium point. If there exists a function $V: R^n \to R$, $V(x) = x^T P x, P \in R^{n\times n}$, positive definite, unbounded and fulfilling 1, 2 and 3:*

1. $F(x) \leq 0, \forall x \in B^0$,
2. $u_i(x) \leq -\frac{F(x)}{B(x)}$ *for* $x \in X_i^A \cap B^+$ *and* $u_i(x) \geq -\frac{F(x)}{B(x)}$ *for* $x \in X_i^A \cap B^-$, $i=\overline{1,r}$,

3. the set $\left\{x \in X \left| \dot{V}(x) = 0 \right.\right\}$ *contains no state trajectories except the trivial one,* $x(t) = 0$ *for* $t \geq 0$,

then the closed-loop system composed by the T-S FLC and the process (1) will be globally asymptotically stable in the sense of Lyapunov at the origin.

Proof. By the definition of V it results that $V(0) = 0$, $V(x) > 0, \forall x \neq 0$ and $V(x) = x^T P x \to \infty$ as $\|x\| \to \infty$. Further on, it will be proved that $\dot{V}$ is negative semi-definite with respect to time employing (7). An arbitrary initial state vector $x_0 \in X$ is accepted. Then the following three cases are possible.

Case 1: $B(x_0)$ is strictly positive. From the condition 2 of Theorem 1 it results that:

$$u_i(x_0) \leq -\frac{F(x_0)}{B(x_0)} \Rightarrow u(x_0) = \frac{\sum\limits_{i=1,\alpha_i \neq 0}^{r} \alpha_i(x_0) u_i(x_0)}{\sum\limits_{i=1,\alpha_i \neq 0}^{r} \alpha_i(x_0)} \leq \frac{-\frac{F(x_0)}{B(x_0)} \sum\limits_{i=1,\alpha_i \neq 0}^{r} \alpha_i(x_0)}{\sum\limits_{i=1,\alpha_i \neq 0}^{r} \alpha_i(x_0)} = -\frac{F(x_0)}{B(x_0)} \Rightarrow$$

$$\Rightarrow \dot{V}(x_0) = F(x_0) + B(x_0) u(x_0) \leq F(x_0) + B(x_0)\left(-\frac{F(x_0)}{B(x_0)}\right) = 0. \tag{10}$$

Therefore,

$$u_i(x_0) \leq -\frac{F(x_0)}{B(x_0)} \Rightarrow \dot{V}(x_0) \leq 0. \tag{11}$$

Case 2: $B(x_0)$ is strictly negative. Once more, from the condition 2 of Theorem 1 it results that

$$u_i(x_0) \geq -\frac{F(x_0)}{B(x_0)} \Rightarrow u(x_0) = \frac{\sum\limits_{i=1,\alpha_i \neq 0}^{r} \alpha_i(x_0) u_i(x_0)}{\sum\limits_{i=1,\alpha_i \neq 0}^{r} \alpha_i(x_0)} \geq \frac{-\frac{F(x_0)}{B(x_0)} \cdot \sum\limits_{i=1,\alpha_i \neq 0}^{r} \alpha_i(x_0)}{\sum\limits_{i=1,\alpha_i \neq 0}^{r} \alpha_i(x_0)} = -\frac{F(x_0)}{B(x_0)} \Rightarrow$$

$$\Rightarrow \dot{V}(x_0) = F(x_0) + B(x_0) u(x_0) \leq F(x_0) + B(x_0)\left(-\frac{F(x_0)}{B(x_0)}\right) = 0. \tag{12}$$

Therefore,

$$u_i(x_0) \geq -\frac{F(x_0)}{B(x_0)} \Rightarrow \dot{V}(x_0) \leq 0. \tag{13}$$

Case 3: $x_0 \in B^0$. In this case using the condition 1 in Theorem 1 the result will be $F(x_0) \leq 0$. Hence,

$$\dot{V}(x_0) = F(x_0) + B(x_0) u(x_0) = F(x_0) \leq 0. \tag{14}$$

From the above three cases it is obtained that

$$\dot{V}(x) \leq 0, \forall x \in X. \tag{15}$$

In conclusion, the derivative with respect to time of the Lyapunov function candidate, $\dot{V}$, is negative semi-definite.

The condition 3 ensures the fulfilment of LaSalle's invariance principle. This justifies the fact that the equilibrium point at the origin is globally asymptotically stable.

The proof is now complete. □

The stability theorem presented here ensures sufficient conditions for the stability of the fuzzy logic control system described in Section 2. So it has been proved that if the Lyapunov function candidate is negative semi-definite in the active region of each fuzzy rule then, the closed-loop system will be globally asymptotically stable in the sense of Lyapunov.

The conditions 1 and 2 in Theorem 1 guarantee that the function $\dot{V}$ is negative semi-definite in the active region of each fuzzy rule. The condition 3 proves that the set $\{0\}$ is the largest invariance set in $\left\{x \in X \left| \dot{V}(x) = 0 \right.\right\}$. By LaSalle's invariance principle it has been guaranteed that the fuzzy logic control system, comprising the nonlinear process described by (1) and the T-S FLC, is globally asymptotically stable in the sense of Lyapunov at the origin.

The stability analysis algorithm ensuring the stability of the class of fuzzy logic control systems considered in Section 2 is based on Theorem 1. It consists of the following steps:

1. Set the Lyapunov function candidate V (i.e. set P).

2. Check that the set $\left\{x \in X \left| \dot{V}(x) = 0 \right.\right\}$ contains no state trajectories except the trivial one, $x(t) = 0$ for $t \geq 0$.

3. Determine $F(x), B(x), B^0, B^-, B^+$.

4. If $F(x) \leq 0, \forall x \in B^0$ then go to step 5. Else go to step 1.

5. For each fuzzy control rule i determine u_i such that $u_i(x) \leq -\frac{F(x)}{B(x)}$ for $x \in X_i^A \cap B^+$ and $u_i \geq -\frac{F(x)}{B(x)}$ for $x \in X_i^A \cap B^-, i = \overline{1,r}$.

The application of this algorithm will be illustrated in the next Section.

4 Illustrative example

This Section is dedicated to the validation of the theoretical results derived in Section 3 by the design of a stable fuzzy logic control system with T-S FLC controlling a nonlinear process, the inverted pendulum on a cart system. This simple mechanical system is representative to model a class of attitude control problems whose goal is to maintain permanently the desired vertically oriented position. Since the inverted pendulum is a nonlinear system, the basic balance equations for the system are derived firstly and put into the standard state-space form. Given an inverted pendulum mounted on a cart as shown in Figure 2, the first principle nonlinear equations are applied in the sequel. Assuming that the rod is massless and that the cart mass and the point mass at the upper end of the inverted pendulum are denoted as M and m, respectively, there is an externally x-directed force on the cart, $F(t)$, and the gravity force acts on the point mass at all times. The coordinate system is defined according to Figure 2, where $x(t)$ represents the cart position and $\theta(t)$ is the tilt angle referenced to the vertical upward direction.

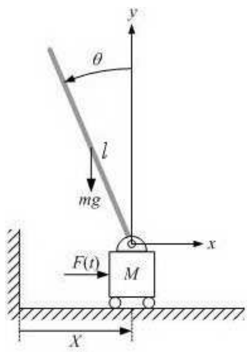

Figure 2: Variables related to the inverted pendulum on a cart system.

The differential equation that describes the behavior of the simplified system, playing the role of controlled process, is usually written as

$$(m+M) \cdot l^2 \cdot \ddot{\theta} - (m+M) \cdot l \cdot g \cdot \sin(\theta) = -u, \tag{16}$$

where:

M - the mass of the cart,

m - the mass of the pendulum,

l - the length of pendulum (distance to the center of mass),

x - the cart position coordinate,

θ - the pendulum angle with respect to the vertical position,

u - the control signal, equal to the externally x-directed force, $u = F$.

The state vector consists of the angle, θ, and the angular velocity of the pendulum, $\dot{\theta}$. Therefore, the two state variables are defined as z_1 and z_2, where $z_1 \in [-80, 80]$, $z_2 \in [-30, 30]$, $z_1(t) = \theta(t)$ and $z_2(t) = \dot{\theta}(t)$. In order to write equation (19) in terms of state variables, they are substituted resulting in

$$\dot{z} = f(z) + b(z)u, \tag{17}$$

where: $z = \begin{bmatrix} z_1 \\ z_2 \end{bmatrix}$ - state vector, $f(z) = \begin{bmatrix} z_2 \\ \frac{g}{l}\sin(z_1) \end{bmatrix}$, $b(z) = \begin{bmatrix} 0 \\ -\frac{1}{(m+M)l^2} \end{bmatrix}$.

The goal of fuzzy logic control system design, to be presented as follows, is to ensure the upright stabilization of the pendulum aiming the setpoint value of z, $z = 0$. The design starts with setting the fuzzification module of the T-S FLC. Figures 3 and 4 illustrates the membership functions corresponding to the LTs of the linguistic variables z_1 and z_2. The three LTs representing Positive, Zero and Negative values are noted by P, Z and N, respectively.

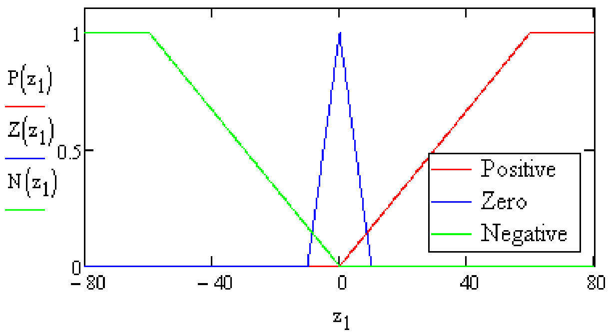

Figure 3: Membership functions of z_1.

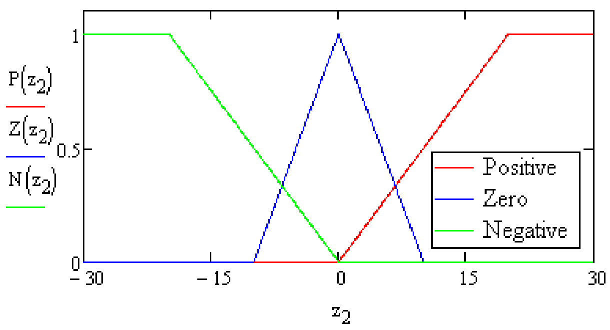

Figure 4: Membership functions of z_2.

The inference engine of the FLC employs the MIN and MAX operators and it is assisted by the complete rule base illustrated in Table 1. The weighted sum defuzzification method is used in the T-S FLC structure. Summarizing, the only parameters to be calculated are the consequents u_i in the 9 fuzzy control rules.

Table 1
Fuzzy Control Rule Base

Rule	Antecedent		Consequent
	z_1	z_2	u
1	P	P	u_1
2	N	N	u_2
3	P	N	u_3
4	N	P	u_4
5	P	Z	u_5
6	N	Z	u_6
7	Z	P	u_7
8	Z	N	u_8
9	Z	Z	u_9

The algorithm presented in Section 3 will be applied as follows in order to find the values of u_i for which the system (19) can be stabilized by the above described T-S FLC.

Step 1: The Lyapunov function candidate $V(z) = z^T Pz = z_1^2 + z_2^2$ is considered, where $P = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$. Therefore V is positive. If $\|z\| \to \infty$ then $V(z) \to \infty$. $V(z) > 0, \forall z \neq 0$.

Step 2: The derivative is $\dot{V}(z) = 2z_2 \left(z_1 + \frac{g}{l}\sin(z_1) - \frac{1}{(m+M)l^2}u\right)$ and $\dot{V}(0) = 0$. Assume that there is a trajectory with $z_2(t) = 0$ and $z_1(t) \neq 0$. Then $\frac{d}{dt}z_2(t) = \frac{g}{l}\sin(z_1(t)) - \frac{1}{(m+M)l^2}u(t) \neq 0$, which means that $z_2(t)$ can not stay constant. Hence, $z(t) = 0$ is the only possible state trajectory for which $\dot{V}(z) = 0$. So the set $\left\{z \in X \,\middle|\, \dot{V}(z) = 0\right\}$ contains no trajectory of the system except the trivial trajectory $z(t) = 0$ for $t \geq 0$.

Step 3: The expressions of F and B are:

$$F(z) = 2z_2\left(z_1 + \frac{g}{l}\sin(z_1)\right), B(z) = -\frac{2z_2}{(m+M)l^2}. \tag{18}$$

The following elements necessary in Theorem 1 obtain the particular values expressed in (23) to (26):

$$B^0 = \{(z_1, 0) \in X \,|z_1 \in [-1, 1]\}, B^+ = \{(z_1, z_2) \in X \,|z_2 < 0\}, B^- = \{(z_1, z_2) \in X \,|z_2 > 0\}, \tag{19}$$

$$-\frac{F(z)}{B(z)} = l(m+M)(z_1 l + g\sin(z_1)). \tag{20}$$

Step 4: If $z \in B^0$ then $z_2 = 0$ and $F(z) = 0$.

Step 5: Each rule will be analyzed further on. This is not a complex task since only 9 rules are involved.

For rule 1: z_1 IS P, z_2 IS P. So $X_1^A = (0, 80] \times (0, 30]$, $X_1^A \cap B^+ = \emptyset$ and $X_1^A \cap B^- = (0, 80] \times (0, 30]$. Thus, $u_1(z) \geq -\frac{F(z)}{B(z)} = l(m+M)(z_1 l + g\sin(z_1))$. It is taken $u_1(z) = l(m+M)(z_1 l + g)$, and this function fulfills the condition 2 in Theorem 1.

For rule 2: z_1 IS N, z_2 IS N. So $X_2^A = [-80, 0) \times [-30, 0)$, $X_2^A \cap B^+ = [-80, 0) \times [-30, 0)$ and $X_2^A \cap B^- = \emptyset$. Thus $u_2 \leq -\frac{F(z)}{B(z)} = l(m+M)(z_1 l + g\sin(z_1))$. It is taken $u_2(z) = l(m+M)(z_1 l - g)$, and this function fulfills the condition 2 in Theorem 1.

For rule 3: z_1 IS P, z_2 IS N. So $X_3^A = (0,80] \times (-30,0]$, $X_3^A \cap B^- = \emptyset$ and $X_3^A \cap B^+ = (0,80] \times (-30,0]$. Thus $u_3(z) \le -\frac{F(z)}{B(z)} = l(m+M)(z_1 l + g\sin(z_1))$. It is taken $u_3(z) = -z_1$, and this function fulfills again the given condition.

For rule 4: z_1 IS N, z_2 IS P. So $X_4^A = [-80,0) \times (0,30]$, $X_4^A \cap B^+ = \emptyset$ and $X_4^A \cap B^- = [-80,0) \times (0,30]$. Thus $u_4(z) \ge -\frac{F(z)}{B(z)} = l(m+M)(z_1 l + g\sin(z_1))$. It is taken $u_4(z) = -z_1$, and this function fulfills the given condition.

For rule 5: z_1 IS P, z_2 IS Z. So $X_5^A = (0,80] \times (-5,5)$. Thus, two possible cases will occur:

$a)$ for $z \in X_5^A \cap B^- = (0,80] \times [0,5) \Rightarrow u_5(z) \ge -\frac{F(z)}{B(z)} = l(m+M)(z_1 l + g\sin(z_1))$ and

$b)$ for $z \in X_5^A \cap B^+ = (0,80] \times (-5,0] \Rightarrow u_5(z) \le -\frac{F(z)}{B(z)} = l(m+M)(z_1 l + g\sin(z_1))$.

In order to satisfy both conditions it is chosen $u_5(z) = l(m+M)(z_1 l + g\sin(z_1))$.

For rule 6: z_1 IS N, z_2 IS Z. So $X_6^A = [-80,0) \times (-5,5)$. The result will be:

$a)$ for $z \in X_6^A \cap B^- = [-80,0) \times (0,5) \Rightarrow u_6(z) \ge -\frac{F(z)}{B(z)} = l(m+M)(z_1 l + g\sin(z_1))$ and

$b)$ for $z \in X_6^A \cap B^+ = [-80,0) \times (-5,0) \Rightarrow u_6(z) \le -\frac{F(z)}{B(z)} = l(m+M)(z_1 l + g\sin(z_1))$.

In order to satisfy both conditions it is chosen $u_6(z) = l(m+M)(z_1 l + g\sin(z_1))$.

For rule 7: z_1 IS Z, z_2 IS P. So $X_7^A = (-10,10) \times (0,30]$, $X_7^A \cap B^+ = \emptyset$ and $X_7^A \cap B^- = (-10,10) \times (0,30]$. Thus $u_7(z) \ge -\frac{F(z)}{B(z)} = l(m+M)(z_1 l + g\sin(z_1))$. It is set $u_7(z) = l(m+M)(z_1 l + g)$ to fulfill the condition 2 in Theorem 1.

For rule 8: z_1 IS Z, z_2 IS N. So $X_8^A = (-10,10) \times [-30,0)$, $X_8^A \cap B^+ = (-10,10) \times [-30,0)$ and $X_8^A \cap B^- = \emptyset$. Thus $u_8(z) \le -\frac{F(z)}{B(z)} = l(m+M)(z_1 l + g\sin(z_1))$. It is set $u_8(z) = l(m+M)(z_1 l - g)$ to fulfill the condition 2 in Theorem 1.

For rule 9: z_1 IS Z, z_2 IS Z. So $X_9^A = (-10,10) \times (-5,5)$. This will yield:

$a)$ for $z \in X_9^A \cap B^+ = (-10,10) \times (-5,0) \Rightarrow u_9(z) \le -\frac{F(z)}{B(z)} = l(m+M)(z_1 l + g\sin(z_1))$ and

$b)$ for $z \in X_9^A \cap B^- = (-10,10) \times (0,5) \Rightarrow u_9(z) \ge -\frac{F(z)}{B(z)} = l(m+M)(z_1 l + g\sin(z_1))$.

In order to satisfy both conditions it is set $u_9(z) = l(m+M)(z_1 l + g\sin(z_1))$.

Concluding, from Theorem 1 it results that the closed-loop system composed by the nonlinear process modeled in (19) and the T-S FLC designed here is globally asymptotically stable in the sense of Lyapunov at the origin. Considering the values of process parameters $m = 0.5$, $M = 0.5$, $l = 1$, $g = 9.8$, the responses of z_1 and z_2 versus time in the closed-loop system are presented in Figures 5 to 8 for different initial conditions.

5 Summary and Conclusions

A new approach to the global asymptotic stability analysis of fuzzy logic control systems employing T-S FLCs dedicated to a class of nonlinear processes has been introduced. The example proves how the stability analysis algorithm suggested here can be applied to the design of a stable fuzzy logic control system for a nonlinear process. The new stability approach can be applied also in situations when the system has an equilibrium point different to the origin and / or the setpoint is nonzero by an appropriately defined state transformation [15].

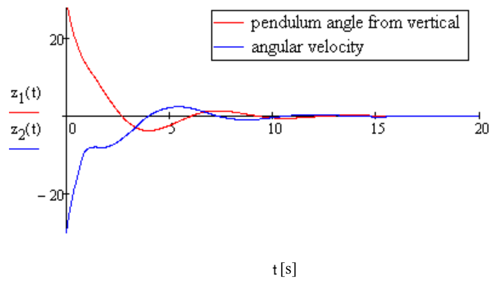

Figure 5: State variables versus time for fuzzy logic control system with T-S FLC in the condition $z_1(0) = 30$ and $z_2(0) = -30$.

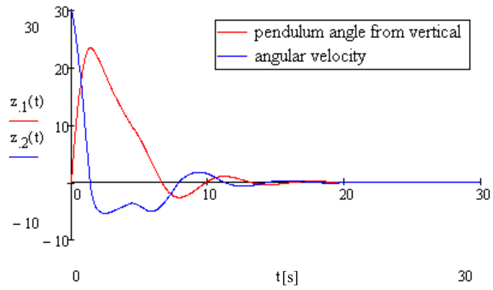

Figure 6: State variables versus time for fuzzy logic control system with T-S FLC in the condition $z_1(0) = 0$ and $z_2(0) = 30$.

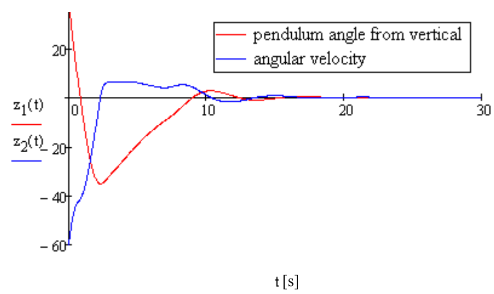

Figure 7: State variables versus time for fuzzy logic control system with T-S FLC in the condition $z_1(0) = 40$ and $z_2(0) = -60$.

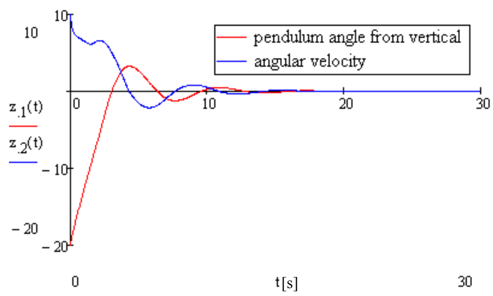

Figure 8: State variables versus time for fuzzy logic control system with T-S FLC in the condition $z_1(0) = -20$ and $z_2(0) = 10$.

The stability analysis algorithm suggested in this paper canbe applied also when the rule base (2) of the T-S FLC is not complete. However interpolation techniques [10, 19] are needed in the implementation of the T-S FLC. They require the re-assessment of the stability conditoins derived prior to the implementation.

Further research will be concentrated on new applications of the proposed algorithm to several classes of processes [4, 5, 7, 8, 9, 17, 20]. The complex applications require the computer-aided design of the Takagi-Sugeno fuzzy logic controllers employing the stability analysis algorithm proposed in this paper to strive for increased generality.

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Fuzzy Controller Based QoS Routing Algorithm with a Multiclass Scheme for MANET

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Abstract: A mobile ad hoc network (MANET) consists of a set of mobile hosts that can communicate with each other without the assistance of base stations. Due to the dynamic nature of the network topology and restricted resources, quality of service (QoS) and multicast routing in MANET are challenging tasks which attract the interests of many people. In this paper, we present a fuzzy controller based QoS routing algorithm with a multiclass scheme (FQRA) in mobile ad hoc networks. The performance of this scheduler is studied using NS2 (Network Simulator version 2) and evaluated in terms of quantitative measures such as packet delivery ratio, path success ratio and average end-to-end delay. Simulations show that the approach is efficient, promising and applicable in ad hoc networks.
Keywords: Mobile ad hoc networks, Fuzzy controllers, Routing algorithm, QoS

1 Introduction

Mobile ad hoc networks (MANET) consist of mobile nodes that autonomously establish connectivity via multihop wireless communications. There is no use of a static network infrastructure such as base station or any centralized administration in MANET. In ad hoc network, if two nodes are not within radio range, all message communication between them must pass through one or more intermediate nodes. All the nodes are free to move around randomly, thus changing the network topology dynamically [1-10]. These type of networks have many advantages, such as self reconfiguration and adaptability to highly variable mobile characteristics like the transmission conditions, propagation channel distribution characteristics and power level. They are useful in many situations such as military applications, conferences, lectures, emergency search, and rescue operations. However, such benefits come with new challenges which mainly resides in the unpredictability of the network topology due to mobility of nodes and the limited available bandwidth due to the wireless channel. These characteristics demand a new way of designing and operating these type of networks. For such networks, an effective routing protocol is critical for adapting to node mobility as well as possible channel error to provide a feasible path for data transmission [1-10].

AODV is an on-demand distance vector routing protocol [2]. The protocol is well known for the use in ad hoc networks. The use of multicasting with the network has many benefits. Multicasting reduces the communication cost for applications that sending the same data to many recipients [3, 5-8]. Instead of sending via multiple unicast, multicast reduces the channel bandwidth, sender and router processing and delivery delay. In addition, multicast gives robust communication whereby the receiver address is unknown or modifiable without the knowledge of the source within the wireless environment.

Quality of service (QoS) support for multimedia applications is closely related to resource allocation, the objective of which is to decide how to reserve resources such that QoS requirements of all the applications can be satisfied [3, 6-11, 16, 21]. The goals of QoS routing are twofold: finding a suitable route through the network between the source and the destination that will have the necessary resources available to meet the QoS constraints; and achieving global efficiency in the utilization of resources. However, it is a significant technical challenge to provide reliable high-speed end-to-end communications in these networks, due to their dynamic topology, distributed management, and multi-hop connections. The provision of QoS requirements is of utmost importance for the development of future networks. For supporting QoS-aware applications, QoS based routing algorithms such as ticket base routing (TBR) [3] and core extraction dynamic source routing (CEDAR) [4] are proposed. In CEDAR, each host compares degree with its neighbors. The host with the largest degrees among its neighbors is selected as the core node. The core node is responsible for recording all information for its members. When a source host requests to establish a QoS routing path to some destination host, its core node must construct a QoS routing path. The advantage of core-based management is that it reduces the number of control packets during path construction. Chang proposes a two-level management approach for efficiently constructing and maintaining a QoS routing path in ad hoc wireless networks, significantly reducing the quantity of control packets [5]. In the first phase, the mobile hosts are partitioned into a number of complete graphs, each represented by a supernode managed by an agent. In the second phase, some agents of a larger degree than neighboring agents are selected as core nodes. Lorenz and Orda demonstrate in the literature [16] that this uncertainty places additional constraints on QoS provisioning. Xiao et al proposed a Dynamic Backup Routes Routing Protocol (DBR2P), a backup node mechanism for quick reconnection during link failures [20]. DBR2P is an on-demand routing protocol and it can set up many routes to reach a destination node in a given period. These algorithms determine a path that satisfies the required QoS.

Fuzzy logic exploits the pervasive imprecision, uncertainty and partial truth of the real world using simple linguistic statements and thereby achieves tractability, robustness, and low solution cost [11, 13-19, 23]. Fuzzy logic based decision algorithm influences caching decisions of multiple paths uncovered during route discovery and avoids low quality paths [11, 14-19]. Differentiated resource allocation considering message type and network queue status is evaluated using fuzzy logic scheme [11]. Fernandez, Hu, kazemian, Zhang et al propose the use of fuzzy logic controllers for the dynamic reconfiguration of edge and core routers [13-15, 23]. This reconfiguration allows for adjusting the network provisioning according to the incoming traffic and the QoS level achieved. Hu and Peter, utilize a self tuning fuzzy controller to apply an end-to-end rate-based feedback flow control algorithm for the available bit rate (ABR) service in ATM [14]. Sheng, et al propose an adaptive routing algorithm in which the link cost was dynamically assigned using a fuzzy system [18]. Their results show the traffic in the networks is rerouted to have less congestion or spare capacity. Sheu and Chen propose a fuzzy bandwidth allocation controller (FBAC) to support services including restricted time-bounded service such as voice and video in wireless networks [19]. Their results show the traffic in the network is rerouted to have less congestion or spare capacity. In those studies, the parameters and rules were further calibrated to obtain a more efficient evaluation. Because the ad hoc network traffics have self-similarity, a common statistical method has been widely used to verify self-similarity of time-series, so that the characteristics of the ad hoc wireless networks can be grasped.

In this paper, we present a Fuzzy controller based QoS Routing Algorithm with a multiclass scheme (FQRA) in mobile ad hoc networks. FQRA proposes to deal with route table management for keeping the active routes' lifetime. FQRA applies a fuzzy logic system to dynamically evaluate the route expiry time. The fuzzy logic is chosen because there are uncertainties associated with node mobility and the estimation of link crash; moreover, there is a mathematical model capable of estimating the node mobility. In addition, FQRA is able to take some controlling factors into consideration. Therefore, FQRA is a multiclass scheme fuzzy evaluation for QoS routing protocol. The performance of the FQRA is studied using NS2 [24] and evaluated in terms of quantitative measures such as improved path success ratio, reduced average end-to-end delay and increased packet delivery ratio.

The rest of the paper is organized as follows. In Section 2, we introduces the ad hoc network model and route issues. In Section 3, we presents the fuzzy QoS controller. In Section 4, we evaluate the performance of the algorithm and present the simulation results. Finally, Section 5 concludes the summary of the work and future challenges.

2 Network Model and Routing Issues

A network is usually represented as a weighted digraph $G = (N, E)$, where N denotes the set of nodes and E denotes the set of communication links connecting the nodes. $|N|$ and $|E|$ denote the number of nodes and links in the network respectively [3-11, 16]. In $G(N, E)$, considering a QoS constrained multicast routing problem from a source node to multi-destination nodes, namely given a non-empty set $M=\{s, u_1, u_2, \ldots, u_m\}$, $M \subseteq N$, s is source node, $U=\{u_1, u_2, \ldots, u_m\}$ is a set of destination nodes. Multicast tree $T= (N_T, E_T)$, where$N_T \subseteq N$, $E_T \subseteq E$, if $C(T)$ is the cost of T, $P_T(s,u)$ is the path from source node s to destination $u \in U$ in T, $D_T(s,u)$ and $B_T(s,u)$ are the delay and usable bandwidth of $P_T(s,u)$.

Definition 1. The cost of multicast tree T is:

$$C(T) = \sum_{e \in E_T} C(e),\ e \in E_T.$$

Definition 2. The bandwidth, and delay route of multicast tree T is the value of link bandwidth, and delay in the path from source node s to each destination node $u \in U$. i.e.

$$B_T(s,\ u)= \min(B(e),\ e \in E_T).$$
$$D_T(s,\ u)= \max(\textstyle\sum_{e \in P_T(s,\ u)} D(e),\ u \in U).$$

Definition 3. Assume the minimum bandwidth constraint of multicast tree is B and the maximum delay constraint is D, given a multicast demand R; then, the problem of bandwidth and delay constrained multicast routing is to find a multicast tree T, satisfying:

(1) Bandwidth constraint: $B_T(s,\ u) \geq B,\ u \in U$.

(2) Delay constraint: $D_T(s,\ u) \leq D,\ u \in U$.

Suppose $S(R)$ is the set, and $S(R)$ satisfies the conditions above; then, the multicast tree T which we find is:

$$C(T) = \min\ (C(T_s),\ T_s \in S(R))$$

3 Fuzzy QoS Controller

3.1 Fuzzy Logic Controller

The fuzzy logic was introduced by Zadeh as a generalization of the boolean logic [22]. The difference between these logics is that fuzzy set theory provides a form to represent uncertainties; that is, it accepts conditions partially true or partially false. Fuzzy logic is a good logic to treat random uncertainty, i.e., when the prediction of a sequence of events is not possible.

Fuzzy logic control system is rule-based system in which a set of so-called fuzzy rules represents a control decision mechanism to adjust the effects of certain causes that come from the system. The aim of the fuzzy control system is normally to substitute for or replace a skilled human operator with a fuzzy rule-based system. Specifically, based on the current state of a system, an inference engine equipped with a fuzzy rule base determines an on-line decision to adjust the system behavior in order to guarantee that it is optimal in some certain senses.

There are generally two kinds of fuzzy logic controllers. One is the feedback controller, which is not suitable for the high performance communication networks. Another one, which is used in this paper, is shown in Figure 1. The output of the fuzzy logic controller in Figure 1 is used to tune the controlled system's parameters based on the state of the system. This control mechanism is different from the conventional feedback control and considered as an adaptive control [11, 14, 19, 23].

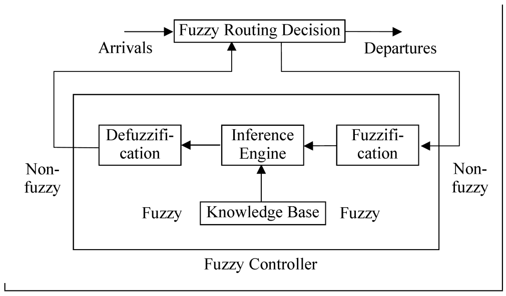

Figure 1: The fuzzy logic controller

The specific features of the fuzzy controller depend on the model under control and performance measurement. However, in principle, in the fuzzy controller we explore the implicit and explicit relationships within the system and subsequently develop the optimal fuzzy control rules as well as a knowledge base.

In the route discovery process, new routes are created. The creation of new routes makes use of forward packet (Table 1) and backward packet (Table 2). A forward packet is broadcasted by the sender and will be relayed by the neighbors of the sender.

When the forward packet reaches the destination node, it extracts the information collected by the forward packet and destroys it and subsequently creates a backward packet which follows the track of the forward packet, but in the reverse direction.

Table 1: Forward packet.

Source address	Destination address	Sequence number
Number of hops	QoS Metric	Intermediate node

Table 2: Backward packet.

Source address	Destination address	Number of hops
QoS Metric	Intermediate node	

The packets flow through router is presented in Figure 2. The aim was to decrease TCP and UDP traffic settling, rise and fall times; decrease overshoots and undershoots; and to stabilize throughput in the router's output connections to let the model adapt for load and link capacity variations.

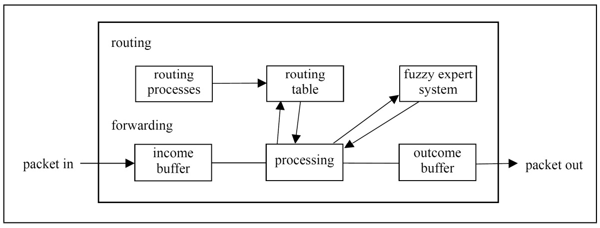

Figure 2: Schematic presentation of packets flow through router

3.2 Scheduler Controller

The packet scheduler used in our architecture is WRR (Weighted Round Robin). In this scheduler, queues are served according to a configurable weight that can be changed during network operation. This allows having control of the bandwidth assigned to each service class. The packet delay and discard rate for each queue (class) can be controlled by changing this weight. An example of membership function of schedule controller is showed in Figure 3. The fuzzy scheduler proposed here calculates the priority index of each packet. Here we consider all the inputs which decide the priority associated with the packet, unlike the previous scheduling schemes. Other membership functions are: packet delay in the expedited forwarding queue and discard rate due to queue overflow in the besteffort class. The output membership functions are also defined as trapezoid functions by the same previous reasons. We make use of the center of gravity defuzzification method, since it gives better results. The output membership function gives the weights assigned to each class in the WRR scheduler.

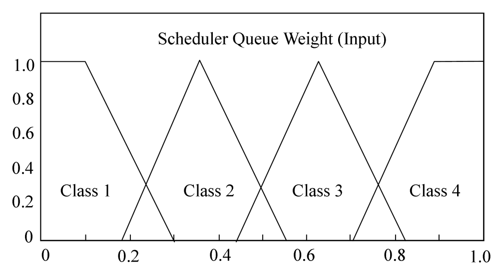

Figure 3: Scheduler membership functions

3.3 Fuzzy Rule Base (Fuzzy Routing)

Fuzzy systems reason with multi-valued fuzzy sets instead of crisp sets. The Fuzzy Logic Controller (FLC) (Figure 1) has two inputs: Residual Bandwidth and Traffic Class and one output: Fuzzy Routing Decision [12, 22].

Mamdani fuzzy-rule based systems constitute of a linguistic description in both the antecedent parts and the consequent parts. Each rule (Table 3) is a description of a condition-action statement that may be clearly interpreted by the users. Rule base is an IF-THEN rule group with fuzzy sets that represents the desired behavior of a fuzzy system. It can be defined in agreement with the administrative policy.

$$\textbf{IF } x_1 \text{ is } A_{i1} \text{ and} \ldots \text{and } x_n \text{ is } A_{in} \textbf{ THEN } y \text{ is } C_i,\ i = 1, 2, \ldots, L$$

where L is the number of fuzzy rules, $x_j \in U_j$, j=1, 2, …, n, are the input variables, y is the output variable, A_{ij} are the fuzzy sets of the input linguistic variable x_j and C_i is called the set of the output linguistic variable y. A_{ij} and C_i are characterized by both membership functions.

Inputs are of the form: x_1 is A'_1, x_2 is A'_2, …, x_n is A'_n where $A'_1, A'_2, \ldots, A'_n$ are fuzzy subsets of U_1, $U_2, \ldots U_n$, which are the universe of discourse of inputs.

Table 3: Fuzzy rule base - QoS classes and application type.

QoS Class	Application Type
1	Video conference
2	SDTV-quality voice
3	CD-quality audio
4	High-quality voice

4 Simulation

4.1 Random Graph Generation

In generating random graphs, we have adopted the method used in Kazemian, where vertices are placed randomly in a rectangular coordinate grid by generating uniformly distributed values for their x and y coordinates [15]. The remaining edges of the graph are chosen by examining each possible edge (u,v) and generating a random number $0 \leq r < 1$. If r is less than a probability function $P(u,v)$ based on the edge distance between u and v, then the edge is included in the graph. The distance for each edge is the Euclidean distance denoted as $d(u,v)$ between the nodes that form the end-points of the edge. We use the probability

$$P(u,v) = \beta \exp[-\frac{d(u,v)}{\alpha L}].$$

where $d(u,v)$ is geometric distance from node u to node v and L is maximum distance between two nodes. The parameters α and β are in the range (0, 1) and can be used to obtain certain desirable characteristics in the topology; parameter α can be used to control short edge and long edge of the random graph, and parameter β can be used to control the value of average degree of the random graph.

4.2 Simulation Model

To conduct the simulation studies, we used randomly generated networks on which the algorithms were executed. This ensures that the simulation results are independent of the characteristics of any particular network topology. Using randomly generated network topologies also provides the necessary flexibility to tune various network parameters such as average degree, number of nodes, and number of edges, and to study the effect of these parameters on the performance of the algorithms. The platform used was the NS2 (Network Simulator version 2) [24]. NS2 is a discrete event simulator targeted at networking research. NS2 provides substantial support for simulation of TCP, routing, and multicast protocols over wired and wireless networks.

Fuzzy Routing Decision was implemented using the Fuzzy Logic Toolbox in MATLAB [25]. The simulator ran with various input configuration settings and the statistics collected were analyzed in comparison with other well-known on demand routing protocol AODV [2].

Our simulation modeled a network of mobile nodes placed randomly within 1000 $\times$ 1000 meter area. Each node had a radio propagation range of 250 meters and channel capacity of 10 Mbps. Two-ray propagation model was used. The IEEE 802.11 distributed coordination function was used as the medium access control protocol. A random waypoint mobility model was used: each node randomly selected a position and moves toward that location with a speed ranging from just above 0 m/s to 10 m/s. When the node reached that position, it became stationary for a programmable pause time; then it selected another position and repeated the process. The simulation was repeated with different seed values. A traffic generator was developed to simulate CBR (Constant Bit Rate) sources. The size of the data payload was 512 bytes. Data sessions with randomly selected sources and destinations were simulated. Each source transmitted data packets at a minimum rate of 4 packets/sec. and maximum rate of 10 packets/sec. Traffic classes were randomly assigned and simulation was carried out with different bandwidth requirements. There were no network partitions throughout the simulation. Each simulation was executed for 600 seconds of simulation time. Multiple runs with different seed values were conducted for each scenario and collected data was averaged over those runs. Table 4 lists the simulation parameters which are used as default values unless otherwise specified.

Table 4: Simulation parameters

Number of nodes	100
Terrain range	1000m × 1000m
Transmission range	250 m
Average node degree	3-5
Node's mobility speed	0-10 m/s
Mobility model	Random way point
Propagation model	Free space
Channel bandwidth	5 Mbps
Links delay	20-200 ms
Traffic type	CBR
Data payload	512 bytes/packet
Node pause time	0-10 seconds

4.3 Performance Measures

The following measures are used in computing the scheduler performance. These measures were derived from one suggested by the MANET working group for routing protocol evaluation.

Packet delivery ratio: Packet delivery ratio is the ratio of the number of data packets actually delivered to the destinations to the number of data packets supposed to be received. This estimate gives us an idea about how successful the protocol is in delivering packets to the application layer. A high value of packet delivery ratio indicates that most of the packets are being delivered to the higher layers and is a good indicator of the algorithm performance.

Path success ratio: The ratio of the number of connection request discover to the destinations to the number of routed connection requests. The successful routing request is defined as the path computed and established by the algorithm satisfies the delay and bandwidth constraints. This number presents the effectiveness of the algorithm.

Average end-to-end delay: This indicates the end-to-end delay experienced by packets from source to destination. The average end-to-end packet delay is computed as the ratio of total end-to-end delays to the aggregate number of packets successfully delivered to the destination nodes during a simulation run. A higher value of end-to-end delay means that the network is congested and hence the routing algorithm does not perform well.

4.4 Simulation Results

In this performance evaluation the following performance measures were evaluated: packet delivery ratio, percentile of path success ratio and edge-to-edge delay. For each evaluation, we used CBR. All simulations started with initial scheduler configuration with 60% of the bandwidth for each class. To eliminate simulation results with an empty network, we started collecting results 30 seconds after the beginning of the simulation.

After optimization procedure was executed, we could verify the result comparing packet delivery ratio, path success ratio, and average end-to-end delay.

Figure 4 shows the performance analysis of the packet delivery ratio vs. network size for the FQRA, AODV, and Non-QoS (not quality of service metric constraints) in ad hoc network. Using Non-QoS constraints algorithm as a base line for comparison, the result shows that both FQRA and AODV are much better than the Non-QoS constraints algorithm, FQRA is considerably better than AODV. This is because that AODV needs to rediscover the route to retransmit data packets that are lost due to the node's mobility or unreal route paths during the communication. The advantage of FQRA is resulted from choosing the right routing path or updating the unreal route paths just in time by the virtue of the suitable route lifetime estimation.

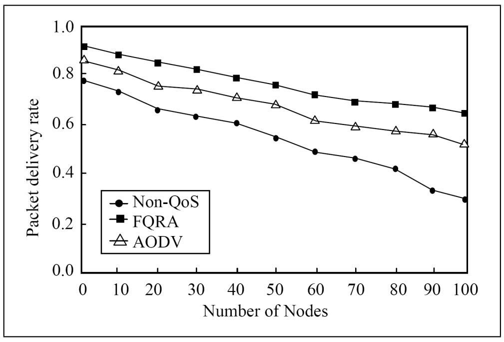

Figure 4: Packet delivery ratio vs. Networks size

Figure 5 shows the comparison of the three algorithms with respect to the average end-to-end delay vs. number of nodes. It shows that the end-to-end delay increases usually with the increasing node. From the Figure 5, we can see that when the nodes increase, FQRA algorithm average end-to-end delay is lower than that of AODV and Non-QoS algorithm. This is because the fuzzy scheduler controller has stability routes and gives more precedence to the packets. Both the AODV and Non-QoS algorithm need more time and more control overhead than the FQRA does to recover unreal paths (broken paths) and to discover new paths. As the nodes increase, more packets are received and thus end-to-end delay increases. The end-to-end delay is important as many real time applications require a small latency to deliver usable data within stipulated period of time.

Figure 6 depicts a comparison path success rate to find the path through FQRA, AODV and Non-QoS in ad hoc network. With the relaxation of bandwidth constraints, the path success rate becomes higher for Non-QoS. The success rate is still higher than that of Non-QoS, which means more suitable for the routing choosing under timely data transmission application and dynamic network structure.

The average and-to-end delay performance as shown in the Figure 7, proves that the end-to-end delay improves when scheduler is included. As the mobility varies from 0-10 m/s, the fuzzy controllers scheduler provides an end-to-end delay reduced by around 0.01 seconds to 0.05 seconds. It shows that the end-to-end delay increases usually with the increasing speed. It also shows that FQRA is much better than the other two. Both the Non-QoS and the AODV need more time and more control overhead than the FQRA does to recover unreal paths and to discover new paths.

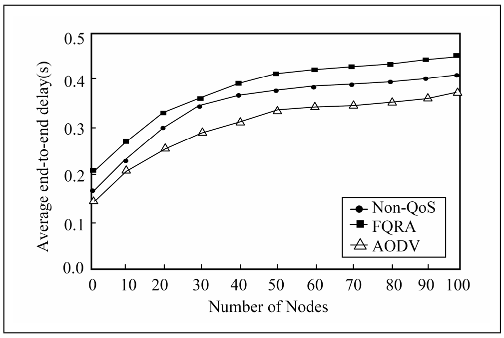

Figure 5: Average end-to-end delay vs. Networks size

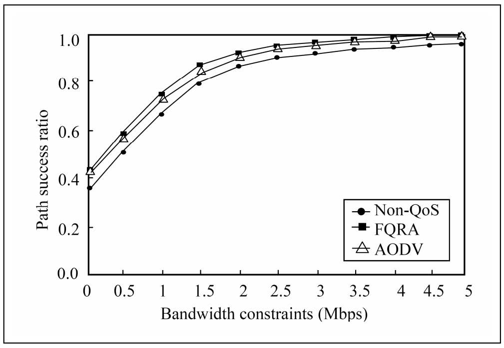

Figure 6: Path success ratio vs. Bandwidth

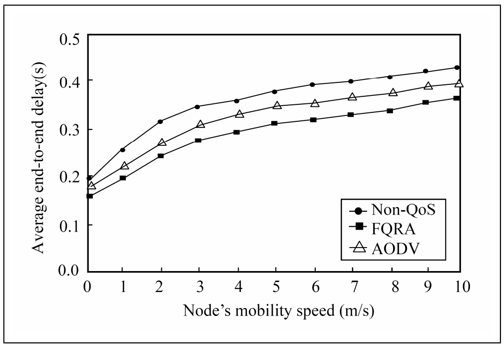

Figure 7: Average end-to-end delay vs. Node's mobility speed

5 Conclusion and Future Work

Our QoS routing algorithm has produced significant improvements in throughput, average end-to-end delay and path success ratio. The fuzzy controllers scheduler algorithm attaches a QoS class to each packet in the queue of the node. Unlike the normal sorting procedure for scheduling packet, the crisp QoS class is calculated by the fuzzy scheduler based on the above inputs which are derived from the network. The membership functions and rule bases of the fuzzy scheduler are carefully designed. The use of fuzzy logic improves the handling of inaccuracy and uncertainties of the ingress traffic into the domain.

In this paper, we present a fuzzy controller based QoS routing algorithm with a multiclass scheme in mobile ad hoc networks. The performance of this scheduler is studied using NS2 and evaluated in terms of quantitative measures such as path success ratio, average end-to-end delay and throughput. Simulation shows that the approach is efficient, promising and applicable in ad hoc networks.

Future work includes comparison with "crisp" versions of the fuzzy algorithm to isolate the contributions of fuzzy logic, as well as applications of fuzzy control to power consumption and directional antennas in MANETs. We also intend to compare FQRA with other QoS routing algorithm.

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MPM Job-shop under Availability Constraints

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Abstract: A large part of scheduling literature assumes that machines are available all the time. In this paper, the MPM Job-shop scheduling problem, where the machine maintenance has to be performed within certain time intervals inducing machine unavailability, is studied. Two approaches to solve the problem are proposed. The first is a two-phase approach where the assignment and the sequencing are solved separately. The second is an integrated approach based on the exact resolution of the 2-job problem using the geometric approach.
Keywords: genetic algorithm, geometric approach, assignment heuristic

Most of scheduling literature assumes that machines are available all the time. However, in many realistic situations, e.g., in typical industrial settings, machine breakdowns and preventive scheduled maintenance have rather quietly common occurrences. These considerations increase the complexity of any scheduling problem but make the problem closer to the industrial reality [26].

In this paper, we consider the job-shop scheduling with Multi Purpose Machines and availability constraints. We consider the deterministic model where the unavailability periods corresponding to maintenance tasks are known in advance. We also assume that preemption of operations is not allowed. More precisely, an operation O_{ij} of job J_i on machine M_k starts only if its execution can be finished before M_k becomes unavailable. The problem considered is a generalization of the classical job-shop problem and the multi-purpose machine problem studied in [12], where machines are available all times.

As compared to the literature dedicated to classical scheduling problems, studies dealing with limited machine scheduling problems are rather rare. Availability constraints have been firstly introduced in single machine [1], [28] and parallel machines [24], [25]. Lee extensively investigated flow-shop scheduling problems with two machines [15], [18], [19]. In particular, the author defined the resumable, non-resumable and semi-resumable models. An operation is called resumable if it can be interrupted by an unavailability period and completed without penalty as soon as the machine becomes available again. If the part of the operation that has been processed before the unavailability period must be partially (respectively fully) re-executed, then the operation is called semi-resumable (respectively non-resumable). Recently, flow-shop scheduling problems with two machines and resumable jobs have been treated in [9] and [14]. Job-shop problem under unavailability constraints has also been considered recently [30], [3] where authors proposed a branch and bound algorithm for the job-shop problem with heads and tails and unavailability periods. The problem considered here is strongly NP-hard since problem without unavailability periods is already strongly NP-hard [12]. In this paper we propose two different approaches to solve this problem.

The remainder of this paper is organized as follows. After a description of the considered problem in the following section, we propose first a two-phase method where a heuristic is used to solve the assignment problem and a genetic algorithm is developed for the sequencing problem. An integrated method, based on the exact resolution of the 2-job problem, is then developed. A comparison between the two algorithms is given in section 4.

1 Problem formulation

The MPM job-shop (job shop with Multi Purpose Machines) with availability constraints ($J(MPM)NCwin \mid C_{max}$: terminology defined in [29]) may be formulated as follows. There are n jobs $J_1,...,J_n$ to be processed on a set of m machines $R = (M_1,...,M_m)$. Each machine M_r can process at most one job at a time. Each job J_i consists of a sequence of n_i operations, that must be accomplished according to its manufacturing process. Each operation O_{ij} $(i = 1,...,n; j = 1,...,n_i)$ can be performed by any machine M_r in a given set $\mu_{ij} \subset R$ for p_{ij} time units. Each operation is non-preemptive, i.e., it must be accomplished without interruption. Moreover, we assume that machine M_r is unavailable during giving periods corresponding to preventive maintenance. The starting times and durations of these tasks are fixed and known in advance. We note K_r the number of maintenance tasks on machine M_r. A_{rl} and D_{rl} represent respectively the starting and the finishing time of the l^{th} maintenance task on machine M_r.
The objective is to find a schedule, defined by the starting time S_{ij} and the completion time C_{ij} of each operation O_{ij}, with a minimum makespan ($maxC_{ij}$).

The scheduling problem in $J(MPM)NCwin \mid C_{max}$ can be decomposed in two subproblems:

- a routing subproblem that consists in assigning operations to machines;
- an operation scheduling subproblem associated with each machine to minimize the makespan. This is a Job-Shop scheduling Problem with Availability Constraints $J,NCwin \mid Cmax$.

2 Two-phase approach for the problem $J(MPM)NCwin \mid C_{max}$

2.1 The routing problem

Since the precedence constraints could be relaxed following the decomposition of the problem in two separate stages, the assignment problem may be treated as a parallel machine problem with the two additional constraints:

- an operation can be performed by a machine belonging to a subset of the set of the available machines: partial flexibility
- machines are subjected to several maintenance constraints: the planning horizon is divided into subintervals

We propose a heuristic based on several priority rules taking into account these two additional constraints.

Assignment heuristic

We use a list algorithm based on priority rules in order to construct an initial assignment solution.
Let us define the following parameters:

- r_{ij}: earliest starting time of operation O_{ij} (definition 1)
- T_k^s availability date of machine M_k at iteration s, where s denotes the iteration number
- ER_k set of operations which can be performed on machine M_k
- EA_k^s set of operations which can be assigned to machine M_k at iteration s
- CM_k^s load of machine M_k at iteration s

Definition 1. To each operation O_{ij}, we associate an earliest starting time r_{ij} calculated by the following formula:

$$\begin{cases} r_{i,1} = 0 \; \forall\, 1 \leq i \leq n \;, r_{i,j+1} = r_{i,j} + p_{i,j} \\ \quad \forall\, 1 \leq j \leq n_i - 1, \; \forall\, 1 \leq i \leq n. \end{cases} \tag{1}$$

- In step 1, the different parameters are initialized.
- In step 2, for each machine we determine the set EA_k^s of operations such that: $r_{ij} \leq T_k^s$.
- In step 3, we evaluate (the potential) starting time of each operation on each possible machine. The availability periods are taken into account. In fact we test if the operation can be scheduled before the next availability period on that machine.

A pair (operation/machine) is selected using the following priority rule:

The less flexible machine M_k ($Min\ CM_k^s$) is selected. Operations in EA_k are sorted in non decreasing order of $card(\mu_{ij})$ (priority is accorded to the less flexible operation). M_k is assigned to the first operation in EA_k which can be scheduled before the next unavailability period.

This priority rule allows occupying the time intervals before the unavailability periods and takes into account the load of machines and the flexibility degree of each operation.

In order to ensure a high level of the solution quality, we have chosen to improve the assignment given by the assignment heuristic. To this end, a local improvement search has been studied. Such search is based on a Tabu algorithm , an adapted routing move technique and an adapted criteria for the studied problem. In next section, we give a description of the Tabu algorithm.

A Tabu Search Algorithm for the assignment problem

Optimization criteria: For a classical routing problem, where machines are available all times, we choose, in general, to minimize the workload of the most loaded machine, since it provides a lower bound for the makespan.

We define, for each assignment S, a lower bound denoted $LB(S)$ for the makespan corresponding to S. This lower bound is based on relaxation into a set of single-machine problems taking into account the unavailability periods. The objective of the tabu search algorithm presented here is to minimize $Cr_1 = LB(S)$ and hence to preoptimize the makespan.

Given an assignment S, we associate with each machine M_k, a single-machine problem π_k with ready times (definition 1), tails (definition 2) and unavailability periods.

A lower bound for π_k is the makespan of a preemptive schedule with unavailability periods, based on the Jackson Preemptive Schedule (JPS) algorithm. Such schedule is calculated for each machine and $LB(S)$ is the maximum makespan value of these schedules.

Definition 2. After the finishing of operation O_{ij} , a time of q_{ij} has to go before job J_i is finished completely. q_{ij} is called the tail of operation O_{ij}

The procedure of preemptive schedule allows constructing the optimal schedule when preempt-resume applies and hence to obtain a lower bound for π_k due to the two following reasons:

1. The unavailability period is treated as an operation, so the problem here is equivalent to the preempt-resume case where JPS gives the optimal solution.
2. The unavailability period will start right on its ready time and will never be preempted since it has the largest tail among the available operations. Preemptive schedule is calculated for each machine and $LB(S)$ is the maximum makespan value of these schedules.

Description of the Tabu Search (TS) algorithm TS was introduced by Glover as a general iterative meta-heuristic for solving combinatorial optimization problems [16]. The TS algorithm is as follows.

- The initial solution is obtained by applying the assignment heuristic described above.

- The solution is described as a list of operations with their corresponding machines.

- A routing move is defined by the relocation of a critical operation (operation that belongs to the critical machine) to a feasible machine position. For a given solution, we consider every possible relocation of every reroutable critical operation.

  The routing move is based on the following steps:

  1. Find the critical machine M_{k_c}.
  2. Find an operation O_{ij} that can be assigned to another machine $M_{k_o} \in \mu_{ij}$ without increasing the criterion value.
  3. Reassign O_{ij} to M_{k_o} if possible.

- The Tabu list consists of pairs $(op; m_o)$, where op denotes the operation that is moved from machine m_o to a different machine.

- The choice of the move is based on the value of Cr_1 which is the maximum makespan value of the preemptive schedules.

2.2 Genetic Algorithm for the sequencing problem

After the assignment step, each operation is assigned to a fixed machine. Thus the MPM job-shop problem is reduced to a job-shop problem with availability constraints (JSPAC).

The problem is then to assign a starting time S_{ij} and a completion time C_{ij} to each operation O_{ij} ($C_{ij} = S_{ij} + p_{ij}$). The considered objective is to minimize the makespan ($C_{max} = max_{i,j}C_{ij}$). We propose a Genetic algorithm to optimize the makespan in a JSPAC.

Coding

According to the literature, two types of approaches exist. In the first, the schedule is directly coded in the chromosome. In the second, a scheduler is associated to the GA to transform the chromosome into actual schedule. In this paper, the latter approach is used to code GA chromosomes. In fact, we use a representation based on job operation. It consists in representing the schedule in a chain of NT operations ($\sum_{1 \leq i \leq n} n_i$) where operations of the same job are represented by the same symbol J_i, the job number. Each job J_i appears exactly n_i times (n_i is the number of operations of J_i) in the chain. For example , for a job-shop problem of dimension 3*3 (3 jobs and 3 operations per job), an example of a chromosome is (1 2 1 3 1 3 2 2 3).

The computation of the starting time and the completion time (S_{ij} , C_{ij}) is obtained according to the order z of each task in the chain (chromosome) and taking into account the unavailability periods of the machines.

Crossover and mutation

We use GOX - Generalized Order Crossover , a swap based mutation and an "Intelligent" mutation operator.

"Intelligent" mutation operator: This operator consists in reducing the idle time before unavailability periods in order to improve the makespan.

This mutation heuristic is described by algorithm 1 and consists in:

For each unavailability period of the critical machine, we exchange an operation scheduled before a maintenance period with another operation which can begin before this maintenance period, but is scheduled after this one. All possible permutations are tested. The permutation minimizing the makespan is selected.

Algorithm 1 Heuristic for the "intelligent" mutation operator

Choose a chromosome X aleatory
calculate the schedule and find the critical machine M_{max}
find OM_{max} : set of operations O_{ij} assigned to M_{max}
For each maintenance period $\mathcal{D}$ of M_{max}
  For each operation O_{ij} in OM_{max} finishing before $\mathcal{D}$
    For each operation $O_{i'j'}$ de OM_{max} which can begin before $\mathcal{D}$ and having been scheduled after $\mathcal{D}$
      Test the permutation of O_{ij} and $O_{i'j'}$
Choose the permutation minimizing the makespan

2.3 Application example

Let us consider an example of a MPM job-shop. It is made of 15 jobs, 5 operations per job and 5 machines. Each machine is subject to two maintenance periods as follows:

M_1: [201 250],[463 512] means that the machine M_1 is unavailable between the dates 201 and 250 and between the date 463 et 512.
M_2: [104 139] , [520 588]
M_3: [233 331], [499 528]
M_4: [137 186], [507 556]
M_5: [129 187], [783 881]

1. Assignment step

   We apply first the assignment heuristic to obtain an initial solution.

   In order to evaluate the solution given by the assignment heuristic, we report in table 1 the load of the different machines as well as the makespan value of the preemptive schedule constructed using Jackson rule.

	M_1	M_2	M_3	M_4	M_5
load	714	782	868	789	839
preemptive schedule	812	907	995	887	997

Table 1: Results of the assignment schedule

2. Sequencing problem

	M_1	M_2	M_3	M_4	M_5
load	815	812	790	818	757
preemptive schedule	913	915	917	916	915

Table 2: Results of the TS algorithm

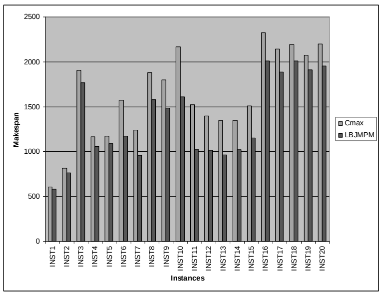

Figure 1: Simulation tests

Table 3 gives the value of the lower bounds based on preemptive schedule for the initial solution of assignment (solution 1) and the solution obtained after applying TS (solution 2) as well as the makespan found by the genetic algorithm.
These results show that TS improves the global solution of the problem and GA gives a good solution comparing to the lower bound. We propose in the next section an integrated approach based on the exact resolution of the 2-job problem.

	solution 1	solution 2
preemptive schedule	997	917
Makespan	1023	968

Table 3: Results of the genetic algorithm

Other experiments were performed on randomly generated instances with more or less availability periods. We report in this section different results for three classes of instances. Each class has five instances. The number of jobs for each class is 10 , 15, 10 and 20 respectively. The number of machines is equal to 5 , 10, 10 and 10 respectively. The processing time for each operation is randomly selected in [|40,150|]. For each machine, the maintenance tasks occur after at least one operation. The starting time for each maintenance task differs from machine to another. The duration of a maintenance task on a machine is the average of the processing times of operations. For the GA, the mutation and crossover probabilities are fixed to: ($P_{crossover} = 0.8$, $P_{mutation} = 0.2$).

In figure 1 we compare the result of the two-phases approach with a lower bound denoted LB_{JMPM} that we have developed for the problem [31].

Comparing with LB_{JMPMAC} our approach gives interesting results (RD_{JMPMAC} 20.6%) with a short computational time. It's worth noting that LB_{JMPM}, which is based on a lower bound for the parallel machine problem, is more interesting for instances with high flexibility.

3 An integrated approach for the $J(MPM), NCwin \mid C_{max}$

This approach is based on the exact resolution of the problem $J(MPM), N_{Cwin}|n = 2|Cmax$. A polynomial algorithm is developed to solve the problem.

3.1 Polynomial algorithm for $J, N_{Cwin}|n = 2|Cmax$

State of the art

The geometric approach has been firstly introduced by Akers and Friedman (1955) in [2]. It consists in reducing the two-job job-shop scheduling problem in the search of a shortest path and thus gives a polynomial algorithm to solve it.

The first step of the geometric approach is the representation of the scheduling problem in a 2-dimensional plane with obstacles, which represent the machine conflict between operations of the two jobs [22]. More precisely,

- Each job J_i is represented by an axe with n_i intervals according to its manufacturing process.
- Each interval corresponds to an operation O_{ij} and has a length of p_{ij} (fig.2).
- Intervals O_{1j} and O_{2k} form an obstacle if O_{1j} and O_{2k} share the same machine (fig.2).
- The horizontal and the vertical crossing the final point F, which corresponds to the completion of the two jobs, are considered as the final obstacle.

A feasible solution of the scheduling problem is then a path going from the origin O to the final point F. Such a path consists of horizontal, vertical and diagonal legs. A horizontal (resp. vertical) leg represents the exclusive progression of job J_1 (resp. J_2), whereas diagonal legs correspond to simultaneous executions of the two jobs. Moreover, any path must avoid the interior of the obstacles. This is due to the fact that two operations can not be executed simultaneously on the same machine and are not preemptable. The length of a horizontal or vertical segment is equal to its usual length while the length of a diagonal segment is equal to the length of its projection in any axe, which is the time spent for the simultaneous processing of two operations.

The shortest path problem in the plane can be transformed into an unrestricted shortest path problem in an acyclic network (see fig.2), where the set of vertices corresponds to the origin O, the final point F and the North-West and South-East corners of the obstacles. Each vertex has at most two successors obtained by going diagonally until hitting an obstacle D. If the obstacle D is the final obstacle, the vertex F is the only successor of node, otherwise the *NW* and *SE* corners of obstacle D, are immediate successors of node (see fig.2).

The Temporized Geometric Approach (TGA), developed by Aggoune [3], [4] is an extension of the geometric approach which exactly solve the problem $J, N_{Cwin}|n = 2|Cmax$. It allows integrating the evolution of time and so the availability of the machines, based on the definition and the introduction of new vertices, as well as a new and dynamic way to progress from one vertex to its successors.

Vertices Characterization and Definitions in TGA: In the classical geometric approach, vertices of the network are the north-west (NW) and south-east (SE) corners of the obstacles hit when going diagonally in the plane. These corners are located at the extremities of the intervals corresponding to operations in conflict. Each vertex can then be defined thanks to its coordinates in the plane: the x-coordinate (resp.

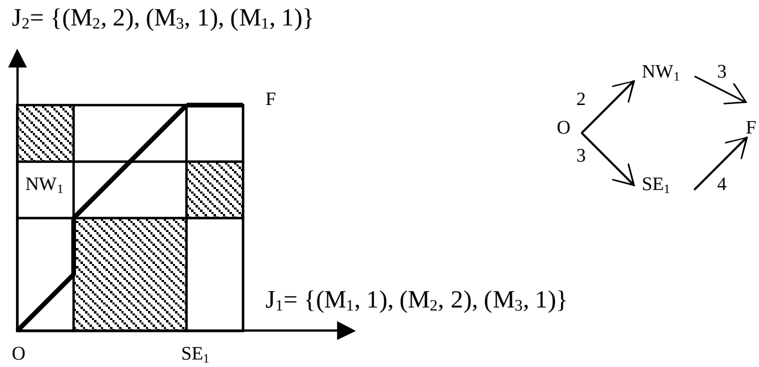

Figure 2: Classic geometric approach

y-coordinate) of the vertex corresponds to operation of job J_1 (resp. J_2) to be executed. In TGA [4], some vertices can be located between two lines bounding an operation, i.e., inside the intervals. For each vertex, each coordinate is additionally attributed by information related to the duration of already processed part of the associated operation. Moreover, an earliest starting time $h(S)$ is associated with each vertex S. $h(S)$is the length of the shortest path from the origin to S.

The set of vertices of the network constructed by TGA is composed by the three following types of vertices:

- Regular vertices, located at the intersection of horizontal and vertical lines, to which *NW* and *SE* corners of obstacles belong.
- Singular vertices, located on a horizontal (resp. vertical) line, which means that the execution of the operation of job J_2 (resp. J_1) has not started yet
- Waiting vertices, also located at the intersection of two lines, for which the execution of operations of jobs J_1 and J_2 has not started yet.

A singular vertex is created if the progression of only one job is possible (availability problem for the other job), whereas waiting vertices are created if the progression is possible for none of the two jobs. A waiting vertex is always a duplication of the regular vertex having the same geometric coordinates but not the same earliest starting time. The progression works as follow:

- If the operations of the two jobs cannot start at time $h(S)$, the earliest starting time of vertex S, a waiting vertex is then created.
- If there is an availability problem in the direction J_1 (resp. J_2), the progression is made along the vertical (resp. horizontal) line, what means that the execution of the operations of job J_2 (resp. J_1) only, until job J_1 (resp. J_2) becomes available. A singular vertex , from which a diagonal progression is possible, is added as successor of S.
- If there is no availability problem, that is to say if the operations of the two jobs can be executed at time $h(S)$, the progression works as in the classical geometric approach.

3.2 An extended approach

We propose a generalization of TGA (GTGA) in order to deal with the flexibility property of the $J(MPM),NCwin \mid n = 2 \mid C_{max}$. This generalization is based on the works of Aggoune [4] and Mati and al. [21] for the flexible Job-shop without availability constraints. As for the job-shop problem, the scheduling of MPM job shop can be represented in the 2-dimensional plane with potential obstacles that depend on the assignment of machines for the two jobs. Let us define the vertices of the network describing the progression in the plane, the successors of each vertex and the distance between any two vertices. We develop the algorithm *SuccVertex* allowing to find the successors of each vertex $S = ((k_1, \Delta^1_{k_1}), (k_2, \Delta^2_{k_2}))$. The algorithm *SuccVertex* is in three steps.

- Step 1 is an initialization step. Set P_h (resp P_v) is defined to keep the machines of job J_2 (resp J_1) allowing to progress until meeting an horizontal and \ or a vertical. This set is used to progress in the next iteration of the program in the case of diagonal progression. E_1 is the set of the possible machines of O_{1v} and E_2 is the set of the possible machines of O_{2h}.

- In step 2, first we check the availability of the two machines for O_{1v} et O_{2h}. If these machines are available, we progress diagonally until a vertical (end of operation of job 1) and or an horizontal (end of operation of job 2) is met depending on the duration of the current operations. Set P_h or P_v is defined to keep the machines of job J_2 or J_1 respectively in the case of diagonal progression. If an availability problem occurs in one of the two directions, the algorithm *SuccVertexAvailability* is used to define the successors of S in this case. The machines concerned by this case are memorized in sets $P_v\_availavility$, $R_h\_availability$, $P_h\_availavility$ and $R_v\_availability$. These sets are used by algorithm *SuccVertexAvailability*. The corners *SE* and *NW* of the potential obstacles that could be reached from S are added as successors of S during the diagonal progression.

- In step 3, we update the current time *current_time*, the sets E_1, E_2, v and h.

The algorithm *SuccVertex* is stopped if the final obstacle is hit or when the diagonal progression is not possible because of availability problems or unavoidable obstacle. The algorithm *SuccVertexAvailability* allows progressing horizontally or vertically (availability problem) until the progression in the two directions becomes possible (end of the unavailability period) , in this case a singular or a regular vertex is added as successor to S ; another availability problem occurs, and in this case a waiting vertex is added as successor of S or an unavoidable obstacle is hit.

Distance Between Two Vertices S and S':

The distance between a vertex v_i and its successor $v_{i'}$ is calculated inside the two developed algorithms using the variable *current_time*. In fact, all machines used to progress from v_i until $v_{i'}$ are fixed. Remark: If F is a successor of S, the distance between S and F is calculated using only available machines, if possible, or machines becoming available first. In fact we neglect the other paths.

Theorem 1. The set of vertices constructed by applying algorithm SuccVertex is sufficient to determine the optimal schedule.

Proof. The correctness of theorem 1 is due to the fact that TGA gives the optimal schedule in the case of classical job-shop [3] and the developed algorithm checks all possible machines for each operation.

3.3 The general job shop problem with multi purpose machine and availability constraints

From the result of the previous section we can deduce a greedy heuristic to calculate a solution for $J(MPM), NCwin \mid Cmax$. This heuristic works as follows:

1. The two first jobs are optimally scheduled using the GTGA algorithm.
2. Additional unavailability periods, corresponding to the execution of operations of the two scheduled jobs, are fixed on each machine.

	Instance size ($nxmxNT$)	Two-phase approach	Integrated approach
Inst1	10x5x50	852	833
Inst2	10x5x50	641	631
Inst3	10x5x50	697	707
Inst4	10x5x50	710	703
Inst5	10x5x50	633	625
Inst6	15x5x75	945	983
Inst7	15x5x75	897	891
Inst8	15x5x75	1023	1017
Inst9	15x5x75	1001	997
Inst10	15x5x75	998	1002

Table 4: Comparison of the two approaches

3. The algorithm is applied to the next two jobs of the sequence, taking into account the initial and the new unavailability periods. This procedure continues until all jobs are treated.

If the number of job is odd we need an insertion procedure to schedule the last job. It is based on the following rule:
An operation of the last job is inserted in such a way, that it begins as early as possible, if we have the choice between two machines we choose the machine giving the smallest idle time.

4 Experimental results

To perform an experimental evaluation of the proposed approaches, we present, in this paper, a ten classical flexible job-shop instances [13]. In order to provide proper experimental settings, two availability periods are generated randomly for each machine. It is worth noting that these results were also confirmed by several other experiments based on randomly generated instances with more or less sizes and/or availability periods [31].

In table 4, we report the values of the makespan given respectively by the two-phase approach and the integrated approach.

These simulations show that the two-phase approach gives interesting results comparing with the integrated approach. The main advantage of the two-phase approach is related to the computation time.

The integrated approach is rather more complicated mainly in terms of computing time. Besides, we note that solutions given by the integrated approach vary with the initial sequence of jobs. Hence, this approach can be improved by adding an optimization algorithm for the initial sequence of jobs. Meanwhile, it appears clearly worth applying this polynomial algorithm in a Branch and Bound algorithm, as done by Jurisch for the classical MPM job-shop without availability constraints [17].

5 Conclusion

We have investigated in this paper MPM job shop scheduling problems under availability constraints. We have proposed two kinds of methods. The first one solves the assignment and the sequencing problems separately. The second one is based on an extension of the geometric approach to deal with the machine availability and the flexibility property of the problem. We are now working on the development of a maintenance management system with an industrial partner including these optimization in a multi-objective environnement. In fact, The analysis of performance of scheduling problem involves more than one criteria [7]. We are focusing on two main criteria : the maintenance total costs and the delivery processes. Other aspects that we will focus on is the real-time approaches to solve schedule problem with unanticipated interruptions [5].

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