CAUSAL MODELS FOR PERFORMANCE EVALUATION OF ADDED-VALUE OPERATIONS

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"Some aspects of the Air Traffic Management
remain cast in stone for decades, whilst other
change more rapidly than the time it takes to write a
book about them"

Andrew Cook

Contents

LIST OF FIGURES

LIST OF TABLES

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INTRODUCTION

"Today, Operations research is recognized worldwide as a modern, decision-aiding science that has proved to be of great value to management, business, and industry... OR problems, OR techniques, and OR solutions are a part of everyone's daily life" [1].

Philip McCord Morse is probably one of the first person to make Operations research (OR) and Systems analysis become an academic discipline to improve decision making in private and public institutions, as well as government. Without hesitation, the operations research discipline was born to handled strategic decisions, resource allocations, optimal scheduling and risk analysis, among others objectives. Its aim was to use the best of human knowledge in a given context and with given time and resources, all in order to provide those in control of the operations with the optimum solutions. The introductory chapter of his book [2] contains a summary of the benefits and possible limitations at applying this newly decision science to the solution of organizations problems in industry, government, private, and public sectors. The foresight of the promise, the difficulties, the necessary ingredients, and the challenge of using scientific models to improve prediction and decision making are well explained too.

Russell Ackoff, David Boodman, Arthur Brown Glen Camp, West Churchman, Les Edie, Martin Ernst, Robert Herman are recognized as some of the pioneering developers of OR. In particular, Russell Ackoff and his mentor, colleague, and friend, West Churchman helped to define OR and its relation to a newly path-breaking approach called "Systems thinking". Churchman state at [3] that *''OR tries to find the best decisions relative to as large a portion of a total organization as is possible... ''OR is the application of scientific methods, techniques, and tools involving the operations of systems so as to provide those in control of the operations with the optimum solutions to the problems.''*

In OR, it is important to perform an appropriate decision making process which identifies the decision variables that are suitable with the objective function, as well as the effect that these variables can cause to the overall performance. Traditionally, a decision is regarded as being a choice: a choice about a course of an action, the choice of a strategy for action, a choice leading to a certain desired objective. [6] These definitions suggest that the decision making process it can be thought as a non-random activity culminating in the selection of one from among multiple alternative courses of action.

Ackoff and Churchman established an innovative form of addressing the decisions making process problems through the System thinking approach. In [4], Ackoff and Emery define a *system* as *"a set of interrelated elements, each of which is related directly or indirectly to every other element, and no subset of which is unrelated to any other subset. A system is an entity composed of at least two elements, and a relation that holds between each* *of its elements and at least one other element in the set. The elements form a completely connected set, which is not decomposable into unrelated sets."*

In this context, the Decisions Making Process has some important features;

- decisions are *time-dependent*, meaning that decisions must be made at the correct moment to achieve its goal, i.e. the same action can be successful under certain conditions and can be useless if these conditions change at any point in time;
- *complex*, in the sense that most decision variables are related or interacting with and/or to each other in one-to-one manner; and
- *dynamic*, because early actions can determine the overall behavior.

The dynamics of the system could shape complex patterns of behaviour where tight coupling decision or action may have unknown effects and an incorrect decision could cause the selection of an expensive or erroneous solution having undesirable consequences. In this regard, complex systems have many interrelated causal relationships that interact between parts of a system and how these relationships lead the overall behaviour of the system. *Emergence* is a property of a complex system that results from the interactions and relationships among its agents (parts), and between the agents and their environment. . An emergent property is often said to be more than the sum of the parts, although it would be more accurate to say that an emergent property is different than the sum of its parts. Consequently, depending on the context, emergent properties can be beneficial but also they can be harmful for example, if they undermine important safety requirements. [6]

The time critical decisions and the flexibility market requirements are some of the key aspects that trigger the growing complexity of industrial operations and thus, its decision making process. In this context, where one or more decision must be made, several feasible solutions have to be analysed and depending on the objective (or objectives); the most acceptable solution should be chosen to conform a strategy that plans for a sequence of actions. One of the main advantages of using this approach is that it can support the specification of system dynamics at both macro and micro level.

In industries such as the Transportation, Manufacture or Service, the decision making process is presented in a variety of complex problems that goes from scheduling, coordination, allocation or distribution of resources, measure performance, design systems or procedures, analysing and forecasting information, or set prices, to mention some of them. Special interest has been placed in the *Decision Support Systems (DSS)* framework to deal with these problems. In a major expansion the DSS field embraced systems designed to support the needs of decision makers.

The concept of DSS is very broad and its definitions may vary depending on the author's point of view. In [5] a DSS is defined as *"an interactive computer-based system or sub-system intended to help decision makers to use more efficiently communications technologies, data, documents, knowledge and/or models to identify and solve problems in a complex decision process"*.

Since the 80s, the DSS began to diverge and specialize in a wide diversity of fields. Alter, one of the pioneers in DSS, suggested in [10] a taxonomy that has been widely used in the DSS field. Alter's categorized the DSS in terms of the generic operations that can be performed by the system which leads to two main distinct types of DSS; Data-oriented (or analysis information systems) and Model-driven (or model-oriented). Data-driven emphasize access to and manipulation of a time series of data. Data-driven provide a high level of functionality and decision support that is linked to analysis of large collections of historical data. Executive information systems are examples of data-driven DSS. Model-driven DSS emphasize access to and manipulation of financial, optimization, and/or simulation models. Model-driven DSS use data and parameters provided by decision makers to aid decision makers in analysing a situation, but generally large data bases are not needed.

Model-driven DSS attempt to abstract the essence of the real problem by imitating the system behaviour. The description of the characteristics of interest is known as the *model*, and the abstraction process to obtain this description is called *modelling*. In other words, these Model-driven DSS do not contain every aspect and detail of the system that they are attempting to imitate, they only describe. a partial fragment of the real world but accurate enough to address the problem situation. Hence, a model might range from a high-level representation to a very detailed one. Modelling is about moving from a problem situation, through model requirements to a definition of what is going to be modelled and how. Models can be built in a variety of ways, and they have different meanings according to the modeller and objectives pursuit. In the same sense, diverse modelling languages are used to formulate and manage models for different purposes and size commonly encountered in industry. Therefore, there is a wide range of definitions and taxonomies for them.

In [7] and [8] Arnott and Pervan traced the evolution of DSS using seven sub-fields in DSS: intelligent, knowledge-driven, executive information systems/business intelligence, data warehousing, personal, group support systems, and negotiation support systems. Even though these sub-groupings overlap, they reflect the diverse evolution of DSS. In recent years, a connection between intelligent and knowledge-driven DSS has been developed.

According to [6], [7] and [8] knowledge-driven DSS have branched out of intelligent decision support. These DSS have been characterized by sequences of actions that can accomplish various tasks. This could include algorithms, instructions, recipes, and plans. Many kinds of characterizations are possible for intelligent and knowledge-driven DSS, including text, decision trees/tables, rule sets, cases, production grammars, neural networks, belief networks, spread sheets with databases, text, and graphical representations, and different causal logic representations being among the most common. Some of these approaches clearly show new modelling formalisms and tools embedded in the DSS, including visual interactive modelling, artificial intelligence tools, heuristics, policies, regulations, rules, knowledge base, voice recognition, neural networks, and diverse meta-heuristics and so forth. In [10], [11] and [12], these DSS are distinguished by being more sophisticated and comprehensive, and by adding capabilities such as satisfying ad hoc knowledge needs, user specific customization of functionality and interfaces, performing knowledge with specialized problem-solving expertise, where the expertise consists of knowledge about a particular domain, understanding of problems within that domain, and skill at solving some of these problems. Consequently, the applications can cover broader domains.

In the work of [9] and [5] diverse intelligent and knowledge-driven DSS have been designed to tackle different applications, such as support operational decision making, financial management and strategic decision-making, inventory management strategies, forecasting tools, etc. Production and Operations management contains the largest number of application articles published, followed by marketing, transportation, and logistics, management information systems, multifunctional systems, finance, strategic management, and human resources. In the logistics and transportation fields, DSS has been introduced in several distinctive processes that involve the integration of information, warehousing, planning for aggregate demand and product planning, capacity/product planning (fixed and adjustable), master scheduling, operations design, scheduling and controlling, inventory management, resource management, among others.

Hence, it is also possible to construct a DSS by modelling and analysing the system behaviour toward establishing cause-and-effect relations of the system. The concepts of causal models in this context refers to a set of cause-and-effect relationships between temporally simultaneous or successive events (causes, occurrence, or states) that produces a phenomenon (behaviour, effect or consequence) where the second event is understood as a consequence of the first. A causal model can be associated with a directed graph in which each node corresponds to a variable of the model and the directed edges (arrows) point from the variables that have direct influence to each of the other variables that they influence.

The present research introduces different case studies to fill the gap between theory and practice for modelling and analysis of Discrete-Event System (DES) as decision support tools in an operational context. The DES are characterized by their states over time; their states do not change continuously but, rather, because of the occurrence of events. This makes them asynchronous, inherently concurrent, and highly nonlinear, rendering their modelling and simulation different from that used in traditional approaches. In order to improve the model definition for this class of systems, a number of techniques can be introduced, including Petri Nets, Finite State Machines, min-max algebra, Timed Automata, etc. Bibliography of this field and other advanced literature include references as [13], [14], [15], [16], [17], [18], [19] or [20] among others.

The Petri Nets (PN) and Coloured Petri Nets (CPN) formalisms are versatile and well-founded modelling languages to be used in practice for systems of the size and complexity found in industry. Coloured Petri Nets is a graphical language for constructing models of concurrent systems and analysing their properties. CPN is a discrete-event modelling language combining the capabilities of Petri Nets with the capabilities of a high-level programming language. Petri nets provide the foundation of the graphical notation and the basic primitives for modelling concurrency, communication, and synchronisation towards a very broad class of systems but it is aimed as a general modelling language, i.e., it is not aimed at modelling a specific class of systems. Both, PN and CPN are employed for describing synchronisation of concurrent processes, but in particular, CPN provide the strength for defining data types and manipulating data values. CPN have been used to verify and validate systems through property analysis and more recently, the state space analysis tool has been used to perform optimization tasks. In this context, the quantitative analysis of state space can be applied in order to develop decision support tools that are capable of facing optimization of industrial problems such as scheduling of activities, resource management and allocation problems, among others. [26], [27], [28], [47] and [48]

Simulation and condensed State Spaces analysis are techniques used to analyse the system behaviour. The use of the State Spaces analysis ensures real optimal configurations when the exploration of the complete state space is possible. The basic idea behind a state space is to construct a graph which has a node for each reachable marking and an arc for each occurring binding element. State spaces are also called occurrence graphs or reachability graphs/trees. The first of these names reflects the fact that a state space contains all the possible occurrence sequences, while the two latter names reflect that the state space contains all reachable states. [26] However, this approach presents the well-known state explosion problem [38], i.e. for many systems; the state space becomes so large that it cannot be fully constructed. Research in this topic has been done and different techniques have emerged. Some of these techniques avoid construction of all the sequences in which concurrent binding elements can be interleaved. It is possible to develop alternative approaches to analyse complex state spaces together with the implementation of searching technique, Heuristics, meta-heuristics or Simulation to explore potential solutions in a more efficient way. [29] and [30]

With the use of the State Space analysis, it is possible to evaluate the different states of a system. The main idea behind this approach is to analyse all possible (reachable) configurations or states changes of the system that can be obtained from an initial state. From a state space it is possible to answer a large set of analysis and verification questions concerning the behaviour of the system such as absence of deadlocks, the possibility of always being able to reach a given state, and the guaranteed delivery of a given service. This approach has been commonly used to verify model’s properties in order to determine the behaviour of the modelled system. [32], [35], [36] and [37]

1.1 Motivation

The success of most industries has been depending on the flexibility to overcome the changing marketing demand and economic factors that all organizations are dealing with. Survival and success is tightly link with astute decision making in this increasingly turbulent and complicated sector. In this regard, the global market requirements must be carefully thought about, observe, study and become familiar with as preliminary preparation to improve the decision making process. Using this knowledge efficient decision support systems can be designed to explore the decision making process for complex situations, understanding and exploring possible scenarios as well as the mechanisms that influence them.

The study of decision support systems is an applied discipline that uses knowledge and especially theory from other disciplines. As Ackoff states in [4], "Managers are not confronted with problems that are independent of each other, but with dynamic situations that consist of complex systems of changing problems that interact with each other." In this regard, diverse disciplines such as statistics, economics or information systems have developed various methods to help in the decision making process. These disciplines have been incorporated and enhanced by a variety of techniques originating from information science, cognitive psychology, and artificial intelligence, among others. The use of knowledge based and optimization approaches have been recognized for its contributions to managerial planning and complex global operations.

In industry, the decision making process concerning complex problems have driven the development of Decision Support tools to achieve optimal or near optimal solutions. Like most of the scientific theories, Decision Support Systems have a broader scope, but the concept of an efficient decision making process constitutes the baseline of this paradigm. Diverse model driven DSS have been developed to support long, medium and short term operations strategies. Model driven DSS lead to a more complete identification and understanding of the requirements to be placed on the system. By investigating a model, similarities can be identified that can be exploited to unify and generalise the design and make it more logical, or to get ideas to improve the usability of the system. The expansion of these decision support tools in the logistic field have experienced historical milestones to face the decision making process, especially in the manufacturing and transportation industry. They have been using for addressing problems from a wide variety of perspectives: from operational to strategic points of view.

Moreover, the design of Decision Support Systems in complex problems is a ground-breaking approach that can cope with a better use of available resources, an increase in the production process and more effective strategies. In this regard, it is necessary to make use of a proper modelling technique that lends itself to those promising solutions by manipulating the model while addressing the problem at the right level of complexity. This modelling technique should also involve the incorporation of decision support abilities to benefit and amplify the capacity for processing knowledge to add value to processes and outcomes of events that occur in varying situations.

Among the key ideas that have been introduced in this research is the use of causal models to provide insights into the behaviour of complex systems and help the user to design effective policies to improve the system performance. Causal models allows us to represent meaningful relationships of events or actions to predict the effects of each action, and, in this way, the results, advantages, disadvantages and implications of decisions are known in advance. This modelling technique can integrate the information provided by the system with a format based on rules, equations, and relations between components. This is done by understanding the behaviour of the system, organizing their operation and activities within a causal framework.

For example, in the Pallet Loading problem case presented in Chapter 4, different loading strategies are proposed to deal with different box sizes in high diversity production systems and distribution centres. The palletizing is an important link in all those logistics areas where orders from customers must be prepared, placing the packages on pallets in an optimal way. A pallet filled in optimal conditions considers different aspects such as time spent in the process, stability and space utilization which is defined to be the percentage of pallet space or volume occupied by the load products. It is easy to note that a higher space utilization factor requires a smaller number of pallets; hence, a higher efficiency in the palletizing is obtained. The strategies generated are designed using specific “rules” or requirements. The CPN is a general purpose modelling language, it is not aimed at modelling a specific class of systems, but is aimed towards a very broad class of systems that can be characterised as concurrent systems. The CPN modelling formalism allows understanding the behaviour defined under certain conditions within which the system is analysed.

Nowadays, simulation and optimization techniques are used in industry to deal with the decision making activity by searching the optimal solutions. The advantages and potential of simulation techniques are increasingly recognized in a wide range of activities. Basically, simulation provides an environment to study the dynamic behaviour of a system under different operating conditions, using continuous, discrete or hybrid models to represent it.

The use of both, simulation techniques and state space analysis facilitate the design and validation of systems, assessment of strategies and with this the decision making process to improve the performance of operations. Simulation models have proved to be useful for examining the performance of different system configurations and/or alternative operating procedures for complex logistic or manufacturing systems. And, with the use of the State Space analysis technique is possible to obtain the best or optimal solutions to a problem.

These reasons have driven the development of decision support tools using causal models in a Discrete Event Systems approach which has led to efficient results in the different case studies presented in this research, which is essential to achieve an adequate level of competitiveness in the actual international industrial market. Therefore, an innovative causal modelling approach to tackle diverse complex problems is presented to enhance the benefits that this methodology embraces. The case of loading pallets in a company trying to develop a new strategy for placement boxes within a truck for being dispatched; or an airline trying to understand how delays propagate within a flow of aircraft, are some of the applications presented in this research.

1.2 Objective

The present research develops/validates a common framework for modelling complex systems using a Discrete Event Systems (DES) approach as a Decision Support System.

The main sub-objectives for this PhD research are the following:

- A unified causal approximation in the development of models to tackle the decision making process.
- Development of algorithms that support the quantitative analysis of a system.
- Apply the algorithms to timed and untimed problems such as the palletizing and the CD &CR problem in the aeronautical field.
- Present the optimal or close to optimal results values for the stated problems.

1.3 Document Structure and Context

The document is organized in four different parts. First, the Chapter called "Modeling Discrete Event Systems" introduces the basic notions and a general perspective on the systems approach. Particular interest has been placed in the Discrete-Event Systems approach, presenting the main features of this formalism. The main theory behind the Coloured Petri Nets approach is presented in Section 2.1.1

Different case studies are provided from Chapters 3 to 5. Chapter 3 presents the work named ***"A CD&CR causal model based on path shortening/path stretching techniques"***, which has been accepted for publication in the Journal *Transportation Research Part C: Emerging Technologies*. This work depicts a groundbreaking approach to alleviate the airspace congestion and to deal with the implications for the planning, design, and management of Air Traffic Control operations. Particular interest has been placed Terminal Manoeuvring Area (TMA) where the traffic conditions impose to take time-critical decisions. Therefore, an appropriate management of arrival operations could alleviate congestion which impacts directly in capacity and efficiency of the overall Air Traffic Management operations. To evaluate the performance of the the resolution strategy to avoid non-efficient procedures, diverse scenarios have been tasted in a busy traffic period at Gran Canaria's airport. The result obtain contribute with the planning and management of Air Traffic Control operations to increase the overall predictability of the Air traffic, with benefit to airlines and airports, among others.

Chapter 4 corresponds to the article ***"Revisiting the pallet loading problem using a discrete event system approach to minimise logistic costs"*** published in the *International Journal of Production Research (IJPR)*. This work presents an innovative and challenging modelling approach to optimize the space and distribution of boxes into a pallet, supporting the inherent box diversity (heterogeneous palletizing problems) of present production and distribution logistic systems. The space utilization is modelled as squares that can be fragmentise and de-fragmentise. In a first approach, the state space analysis is performed to evaluate different optimal configurations to load the maximum number of boxes on a rectangular pallet. The second approach implements heuristics to show that acceptable occupancy results can be obtained without requiring the exhaustive evaluation of the different feasible combination.

Chapter 5 introduces the work ***"Integrating and sequencing flows in terminal maneuvering area by evolutionary algorithms"*** in proceeding of the IEEE/AIAA en el Digital Avionics Systems Conference (DASC), 2011. This work has received three mentions: Best student paper award; Best paper in the ATM Capacity Improvements track award; y Best paper of session award which confirm the transcendence and implications of such approach. This chapter presents a new approach to optimize a set of aircraft planned to land at a given airport. It is proposed to merge the incoming flows from different routes by mean of speed and path changes. Those changes aim to remove conflicts at merging points and to maintain separation of aircraft following the same route link according to their wake turbulence constraint. The optimization criteria are based on the minimum deviation from the initial path planning. This algorithm has been successfully applied to Gran Canaria airport in Spain with real traffic demand samples for which conflict free flow merging is produced smoothly with optimal runway feeding.

Finally, Chapter 5 contains the overall conclusions, future work, summary of contributions and complementary publications on the author.

The work presented in annex called ***"Causal model to sequence and merge 4DT flows in TMA"*** summarizes the development of a decision support algorithm to tackle the merging and sequencing problem within the Terminal Manoeuvring Area (TMA) sector. The algorithm works with multiple landing traffic flows that share the airspace in the same time window. A flexible terminal area route structure is proposed; it eliminates conflicts within the Standard Terminal Arrival (STAR) while traffic is merged prior converging on to the final approach. As a first instance the first come first serve (FCFS) sequence policy will be tasted and later on the sequence will be altered by means of the Constrained Position Shifting (CPS) algorithm. Gran Canaria STAR is used to evaluate the benefits of the proposed model under synthetic traffic; and to determine the spacing buffers the ICAO Separation minima (ICAO DOC-4444) criteria is used as on current methodology.

Finally, in Annex, the paper "***A TMA 4DT CD/CR causal model based in path shortening/path stretching techniques"*** introduces the basic ideas behind a discrete event model for Conflict Detection and Conflict Resolution algorithm in a TMA 4D trajectory scenario in presented which focuses mainly on the arrival phase. This model brings a very interesting knowledge about the events that take place in the management of 4DT and their interactions in Gran Canaria TMA to remove non-effective operations, avoid delay propagation between arrivals and optimize the occupancy of the runway. The causal model developed considers different alternative predefined turning points for each flight evaluating path shortening/path stretching of all trajectories upwards the merging point in a TMA.

2 MODELING DISCRETE EVENT SYSTEMS

Systems science, with such an ambition and with its basic Systems Theory, provides a general language with which to tie together various interdisciplinary areas. It was gradually accepted that systems are wholes which cannot be understood through analysis inasmuch as their primary properties derive from the interactions of their parts. Systems Theory was founded on the assumption that all kinds of systems had characteristics in common regardless of their internal nature. Systems Theory is a theory across most other disciplines linking closely. Systems Theory uses various ways in classifying systems but in each can be seen, that it is the relationships between components in the system and not the nature of its individual components that proliferate its properties and behaviour. As a basic science, Systems Theory deals, on an abstract level, with general properties of systems, regardless of physical form or domain of application, supported by its own metaphysics. [21]

There is a large literature in Systems Theory, the author refers to [3], [4] and [21] to mention some survives. Some continuously growing literature in *Discrete Event Systems (DES)* and *Coloured Petri Nets (CPN)* is found [13], [14], [15], [16], [17], [18],[17], [19] for a brief introduction to Discrete Event Systems; and in [25], [26], [27], [28], [29], [30], [31], [33], [34] and [35] the Coloured Petri Nets literature can be found. This chapter aims to introduce some basic foundations necessary to follow Chapters 3 to 5, where the case studies of this research are introduced. Many contributions have been done in the DES field.

According to [13], systems can be classified by a time base and looking to the evolution of the properties of interest as *Continuous* or. *Discrete*. In a continuous system the state variables evolve continuously over time. These are called “continuous variables” in the sense that they can take on any real value as time itself “continuously” evolves. In a discrete system, the state variables change only at a certain instant or sequence of instants (discrete set of points in time) and in the middle, during these changes the state variable values remain constant.

It is important to note that it is possible to describe a continuous system using a discrete model and vice versa, it is also possible to describe a discrete system by a continuous model. The decision to use a continuous or discrete model depends on the particular objectives of each study rather than the characteristics of the system. Discrete systems, as well as other types of systems can be represented by models. Thus, models can be used to experiment with a representation of the system (instead of experiment with the system itself). Different types of models can be pointed out; they depend on the purpose of investigation. [13] The choice of whether to use one or other type of model is a function of the characteristics of the system and the objective of the study. In this research, the dynamics of a system are modelled as a series of discrete events at which the state of the system changes.

The main elements of interest in a system are:

- *Entities*: A set of objects that constitute or flow through the system, each of which possess properties of interest. Entities can be temporal or permanent.
- *Attribute*: An attribute denotes the property of an entity that allows the characterization of entities. Each attribute belongs to a property or information attached to the system and they are essential to control the entities.
- *State of the System*: Systems have an unlimited number of properties but only some of these are relevant to any particular research. The state of a system is defined as the minimum collection of relevant variables necessary to describe or characterize all the elements of interest in a system at any time instant. In other words, state of the system mean a description of *state variables.*
- *Event:* An event is defined as an instaneous occurrence that may change the state of the system. An event should be thought of as occurring instantaneously and causing transitions from one state value to another. An event may be identified with a specific action, it may be viewed as a spontaneous occurrence dictated by nature or it may be the result of several conditions which are suddenly all met.

According to [15], the Event-based models frequently use a graph-based notation with nodes representing events (i.e., the state changes that occur when there is a particular kind of event detected) and links representing the relations between those events. The state changes are associated with each event, and the links can have logical relations associated (defining the relations between events). Therefore, models to represent the dynamics of a system as a series of discrete events that perform changes in the state of the system are called modelling oriented to discrete events systems.

Yet another way to classify systems is based on the nature of the state space selected for a model. *"In continuous-state models the state space X is a continuum consisting of all n-dimensional vectors of real (or sometimes complex) numbers. Normally, X is finite dimensional (i.e., n is a finite number), although there are some exceptions where X is infinite-dimensional."* And *"In discrete-state models the state space is a discrete set. In this case, a typical sample path is a piecewise constant function, since state variables are only permitted to jump at discrete points in time from one discrete state value to another."* [16]

2.1 Discrete event systems

Since the 60s, diverse techniques for discrete-event systems (DES) became very popular, and in many cases, this resulted in the definition of an advanced field of research. The Discrete Event System aims to model and describe the occurrence of finite number events in a discrete time base, (i.e. events happen in a continuous time base, but during a bounded time-span, only a finite number of relevant events occurs). These events can cause a change in the state of the system. In between events, the state of the system does not change. [13], [14], [15] Discrete-event formalisms help to develop a high level of abstraction appropriate for realistic representation of a system's behaviour. [17], [18], [19] According to [16], there are different methodologies for modelling and analysing DES, among them it is worthy to mention:

- An automaton
- Timed automata
- Finite state machines (FSMs)
- A Markov chain
- Generalized Semi-Markovian Process
- Petri Nets
- Coloured Petri nets

2.1.1 COLOURED PETRI NETS

Petri nets were developed and named after Carl A. Petri who published in his PhD dissertation [22] a netlike mathematical tool for the study of communication with automata. There are a variety of books about Petri Nets (PN), an introduction to PN can be found in [21], [22], [23], [24] or [25], among others. The last versions of bibliography can also be found in the Advances in Petri Nets Journal, Petri Nets World web page, or Petri Nets Newsletter, among others.

The CPN is a modelling formalism that provides the basic primitives for modelling concurrency, communication, and synchronisation. Typical application domains of CPN are manufacturing systems, communication protocols, data networks, distributed algorithms, business processes and workflows, agent systems and embedded systems.

Abstracting from [31], [33], [34] and [35], the ***Coloured Petri Nets (CPN)*** combined the strength of Petri Nets with the strength of complex data types (as in programming languages). Petri Nets provide the primitives for the description of the synchronisation of concurrent processes, while programming languages provide the primitives for the definition of *data types* and the manipulation of their *data values*. Each CPN can be translated into a PN and vice versa, however, the expressive power of the CPN constitute one of its advantages to model in a more compact and convenient manner.

In contrast to most specification languages, Petri nets are state and action oriented at the same time – providing an explicit description of both the states and the actions. This means that the modeller can determine freely, at a given moment to concentrate on either states or on actions. Coloured Petri Nets have got their name because they allow the use of tokens that carry data values (colours) and hence be distinguished from each other – in contrast to the tokens of Petri Nets.

The CPN language has few, but powerful modelling primitives, which means that relatively few constructs must be mastered to be able to construct models. The modelling primitives also make it possible to model systems and concepts at different levels of abstraction. Formally, a Coloured Petri net is defined as follows:

Definition: The non-hierarchical CPN can be defined by a tuple:

$$TCPN = (\sum, P, T, A, N, V, C, G, E)$$

Where:

$\sum$: is a finite set of non-empty types or colour sets.

P : is a finite set of places.

T : is a finite set of transitions T such that: $P \cap T = \emptyset$

A : is a finite set of arcs such that:

$$P \cap T = P \cap A = T \cap A = Ø.$$

N : is a node function. It is defined from A into $P \times T \cup T \times P$.

V : finite set of typed variables such that Type [υ] $\in \sum$ for all variables $\upsilon \in$ V.

C : P $\rightarrow \sum$ is a colour set function assigning a colour set to each place.

G : T $\rightarrow$ EXPR is a guard function assigning a guard to each transition T such that

$$\forall\ t \in T: [Type(G(t)) = B \wedge Type(Var(G(t)))\ \Sigma]$$

E : is an arc expression function assigning an arc expression to each arc *a,* such that:

$$\forall\ a \in A: [Type(E(a)) = C(p)_{MS} \wedge Type(Var(E(a))) \subseteq \Sigma]$$

Where p is the place connected with the arc *a*

EXPR denotes the expressions provided by the inscription language, and TYPE[*e*] denotes the type of an expression $e \in$ EXPR, i.e. the type of values obtained when evaluating *e*. The set of variables in an expression *e* is denoted VAR[*e*] and the type of a variable *v* is denoted TYPE[*v*].

The *untimed marking* M^U of a TCPN model is a function $M^U : P \rightarrow EXPR$ that maps each place *p* into a multi set of values of values $M^U(p)$ representing the untimed marking of place *p* and $M^U(p) \in C(p)$. In this case the expressions do not contain any time information.

In an informal definition of the main CPN components that fulfil the modelling requirements are:

- ***Transitions:*** The *actions* or *events* of a CPN are represented by means of transitions (drawn by rectangles).
- ***Places***: The possible states of a CPN are represented by means of places (drawn by circles or ellipses). They are very useful to specify both queues and logical conditions. Each place has an associated data type determining the kind of data which the place may contain.
- ***Colour Sets & Colours***: Each place has an associated *data type* determining the kind of data which the place may contain. These data types are usually referred to the token values as token *colours sets* and to the data values as *colour*. The Colour sets will allow the modeller to specify the entity attributes (colours) as well as determinate operations and functions that can be used by the elements of the CPN model. The colour sets of a CPN can be arbitrarily complex, e.g., a record where one field is a real, another text string and a third a list of integers. The set of free variables V are the ones that take values over the correspondent colour set where they participate
- ***State Vector:*** A state vector of a CPN is called a *marking* which is the information needed to predict the events that can appear. It consists of a number of *tokens* positioned on the individual places. Each token carries a data value which belongs to the type of the corresponding place. A marking of a CPN is a function which maps each place into a multi-set of tokens of the correct type (i.e. is a particular configuration of tokens in places). The initial marking M0 is specified by means of the initialisation expressions (which by convention are written with an underline, next to the place). A missing initialisation expression implies that the initial marking of the corresponding place is empty, i.e., contains no tokens.
- ***Guards function*** assigns to each transition (*t*) a guard *G(t)* which is an expression whose evaluation is required to be a Boolean expression. The set of variables that appear in the guard expression is required to form a subset of V.
- ***Input Arc Expressions:*** The input arc expressions will allow specifying the event pre-conditions, i.e. which type of tokens can be used to activate an action or event (fire a transition).
- ***Output Arc Expressions:*** The output arc expressions will allow specifying which actions should be coded in the event routines associated with each event. They are also used to indicate the system state change that appears as a result of firing a transition.
- ***Input place nodes*** of a transition are the ones whose directed arcs end in the transition.
- ***Output place nodes*** of a transition are those in which the directed arcs of the transition end.

An incoming arc indicates that the transition may remove tokens from the corresponding place while an outgoing arc indicates that the transition may add tokens. The exact number of tokens and their data values are determined by the arc expressions. It is said that a transition occurs or is fired when all its values are bind to a value otherwise, the expressions cannot be evaluated. If the binding element occurs, it removes tokens from its input places and adds tokens to its output places. A CPN can “move” the tokens from one place to another, possibly with some change of their data values. However, in the mathematical formulation of a CPN model there is no connection between particular input tokens and particular output tokens. The number of output tokens may differ from the number of input tokens and they may have data values which are of different types.

In the CPN formalism, the terms: type, value, operation, expression, variable, binding and evaluation are used in the same context as these concepts are used in functional programming languages. However, the correct abstraction from colours cannot be fulfilled until the moment when the properties of a CPN have been formulated. It is said that a transition is *enabled* if it is possible to find a binding of the variables that appear in the surrounding arc expressions of the transition such that the arc expression of each input arc evaluates to a multi-set of token colours that are present on the corresponding input place and the correspondent tokens are ready. Each time a transition is *fired* it will remove from each input place the multi-set of tokens to which the corresponding input arc expression evaluates. Analogously, it will add to each output place the multi-set of tokens to which the corresponding output arc expression evaluates and it will attach timestamps to the created tokens. Following these rules, systems’ evolution is modelled with token consumption and creation together with the time elements when a transition is fired. [30]

The CPN are commonly graphically represented by a set of place (circles) and transition nodes (rectangles or solid lines) connected with directed arcs (Figure 2-1).

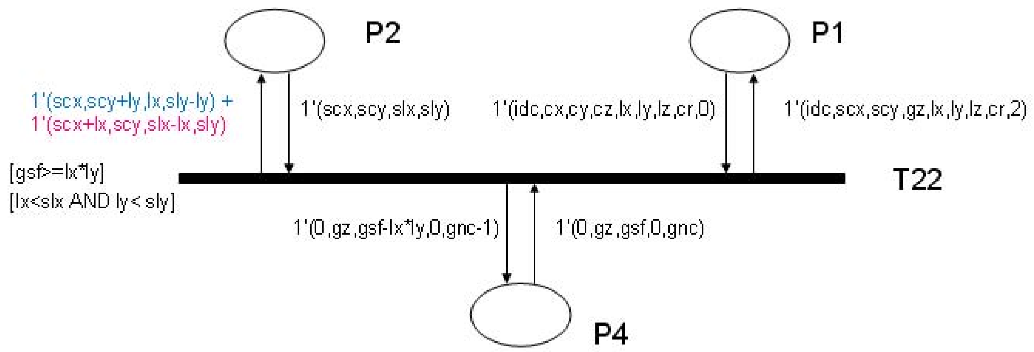

Figure 2-1: Example used to illustrate a CPN

Time plays a significant role in a wide range of concurrent systems. The correct functioning of some systems depends crucially on the time taken by certain activities, and different design decisions may have a significant impact on the performance of a system.

CPN include a concept of time that makes it possible to capture the time taken by events in the system. This time concept also means that CPN can be applied to simulation-based performance analysis, where performance measures such as delays, throughput, and queue lengths in the system are investigated, and for modelling and validation of complex timed systems.

Simulation and State Space

The behaviour of a CPN model can be analysed, either by means of simulation, state space analysis or by means of formal analysis methods. The process of modelling and performing the analysis usually brings diverse benefits that range from an improved understanding of the system, i.e. new insights into the design and operation of the system considered to a more complete specification, identification and understanding of the requirements to be placed on the system.

Nowadays, modelling and simulation provide a well-developed and well proven approach to problem solving that advances steadily as more computing power becomes available at less cost. The basic idea of simulation-based performance analysis is to conduct a number of lengthy simulations of a CPN model, during which data is collected from the occurring binding elements and the markings reached in order to calculate estimates of performance measures of the system. [26] and [48] The typical performance measures include average queue lengths, average delays, and throughput. Simulation-based performance analysis also involves statistical investigation of output data, the exploration of large data sets, appropriate visualisation of performance-related data, and estimating the accuracy of simulation experiments. Simulation output data exhibit random behaviour, and therefore appropriate statistical techniques must be used both to design and to interpret simulation experiments.

By performing simulations of the CPN model, it is possible to investigate different scenarios and explore the behaviour of the system. Very often, the goal of performing simulations is to debug and investigate the system design. Simulation usually leads to significant new insights into the design and operation of the system considered. Gaps in the specification of the system will become explicit as they will prohibit the model from being executed because certain parts are missing, or when the model is simulated, the designers and users will find that certain expected events are not possible in the current state. Since the modeller is able to control the execution of a model, unlike the real system, problematic scenarios can be reproduced, and it can be checked whether a proposed modification of the design does indeed fix an identified error or improves the design in the way intended. [27]

Checking a number of different scenarios by means of simulations does not necessarily lead to correct designs, there may simply be too many scenarios to investigate or the modeller may fail to notice the existence of some important scenarios. The simulation generated data is used to estimate the measures of performance of the system. However, a systematic investigation of scenarios often significantly decreases the number of design errors.

Furthermore, many design problems and errors can be discovered and resolved in the requirements and design phase rather than in the implementation phase. For testing purposes, the modeller typically sets up appropriate breakpoints and stop criteria. For performance analysis the model is instrumented with data collectors to collect data on the performance of the system. [29] and [47]

The CPN formalism has a mathematical definition of both its syntax and its semantics. Such models can be manipulated to verify system properties, i.e., prove that certain desired properties are fulfilled or that certain undesired properties are guaranteed to be avoided. The formal representation is the foundation for the definition of the various behavioural properties and the analysis methods. Formal verification is, by its nature, different from and supplements the kind of informal analysis performed when individual scenarios are inspected by means of simulation. Verification of CPN models and system properties is supported by the state space method.

The *state space* in CPN is also called *reachability tree* or *occurrence graph.* The basic idea of state spaces is to calculate all reachable states (markings) and state changes (occurring binding elements) of the CPN model and to represent these in a directed graph where the nodes correspond to the set of reachable states and the arcs correspond to occurring binding elements. Hence, the state space contains all the possible occurrence sequences and reachable states that can be reached from an initial (known) state. The state space is typically characterized by thousands of nodes and arcs. Therefore, state space methods are closely tied to supporting computer tools. It is possible to analyse and verify an abundance of properties of the system such as *reachability*, *boundedness*, *liveness*, among others. [29], [31], [30] and [34] Different software tool set commercial and academic for graphical editing, simulation, analysis and synthesis of PN and CPN have been developed, as example it can be mentioned [35], [40], [41], [42], [43], [44], [45] and [46]

It should be stressed that for the practical use of CPN there are diverse supporting computer tools that can cope with simulation but also with the state space analysis. The practical application of CPN typically relies on a combination of simulation and state space analysis to evaluate the performance of the system. It is possible to build state spaces by a collection of advanced state space methods which are supported by some CPN computer tools. The advanced methods make it possible to alleviate the impact of the state explosion problem, which is particularly evident when state space analysis of large CPN models is conducted.

State Space analysis can be supported by causal models developed through the CPN formalism. The main advantage of the state space of a CPN is that it contains all the events that could appear according to a particular system state; and, that all the states can be reached starting from the initial marking of the system through directed arcs. Consequently, the event (transition) sequence to be fired drives the system from a certain initial state to a desired end-state. Furthermore, information about the elements (tokens and transitions) that activate the event can be obtained.

3 A CD&CR CAUSAL MODEL BASED ON PATH SHORTENING/PATH STRETCHING TECHNIQUES

Abstract

Some attempts have been done to alleviate the airspace congestion in Terminal Manoeuvring Area (TMA): reduced vertical separation minima, negotiation of voluntary reductions in scheduled service, construction of additional runways at major airports. However, there is still a pending matter to be solved regarding the efficiency of the airspace use, by avoiding non-efficient procedures such as holdings. In line with the requirements of the future air traffic management (ATM) concepts proposed by SESAR and NextGen, the air-traffic flow needs to be more predictable to offer the possibility of more effective use of airspace and airport capacity. In the context of SESAR, 4D trajectory management is expected to improve air traffic operations, in particular to increase the overall predictability of traffic, with benefit to airlines and air traffic management. A deep knowledge concerning the events that take place in the air traffic management of 4D trajectories and their interactions in a TMA is essential to remove non-effective operations, avoid delay propagation between arrivals and optimise the occupancy of the runway. The present paper describes a discrete event model, based on Coloured Petri-Nets formalism, useful to specify a conflict detection and conflict resolution algorithm focusing on the arrival phase of flight. The causal model developed considers different alternative pre-defined turning points for each flight by evaluating path shortening/path stretching of all trajectories upwards the assigned merging points in a TMA.

3.1 Introduction

EUROCONTROL and the FAA are shifting the paradigm of the ATM system, specially the current ATC system. The Terminal Manoeuvring Area, or Terminal Control Area (TMA) is perhaps, the most complex type of airspace and therefore, needs special attention. Congested TMA are being forced to accept more flights each day, and departure pushes to accommodate late arriving flights causing further up and down-line disruptions. With regards to TMA, it is intended to include new concepts, procedures and tools that can improve airspace efficiency using emerging technologies, for example, reduction of additional spacing buffer; modification of procedures and airways' constraints such as; modifying the shape of existing sectors or even the addition of new ones; modifying or adding routes or changing some procedures to improve flexibility; flight crews resolving conflicts without the assistance of air traffic controllers. For this, the use of new communications protocols (e.g., datalink), navigation (e.g., GPS), surveillance (e.g., ADS, TCAS IV) or even Broadcast Services, among others, must be completely available.

Within TMA, aircraft navigate over established Standard Terminal Arrival Route (STAR) from the metre fix to about 10–15 nm radial distance from the airport. In general, arrivals enter TMA at an altitude of 30,000 [ft]. In this area, the control of aircraft flow essentially relies on the use of open-loop radar vectors (heading instructions). Numerous actions are required to fine tune the landing sequence while integrating different traffic flows. Conventional operating methods use vectorization in order to deviate aircraft from their route in order to maintain a safe separation between aircraft. This control could include a complete lateral path to the final approach course, plus a vertical profile (speed and altitude), all of which become part of the arrival clearance. Although this method is efficient and flexible, it is highly demanding for air and ground sides under high traffic load conditions, as it imposes short time for the controller to take a decisions and time-critical execution by the flight crew. Flexibility is without a doubt, one of the main characteristics of this method but flexibility is not always synonym of capacity and performance improvements if the right decisions are not taken.

Special emphasis within TMA is to implement and/or improve procedures as the RNAV and/or RNP Standard Terminal Arrival (STAR), Standard Instrument Departure (SID) and Continuous Descent Approaches (CDA), and to introduce RNAV and/or RNP routes into the en-route airspace. Most airports already have some degree of CDA procedures in low traffic conditions or at night. Flying efficient CDA from cruise altitudes to touchdown are a capability for most Flight Management Systems (FMS) in use. With the use of modern FMS/autopilot-coupled, aircraft are able to fly Required Navigation Performance (RNP) achieving their desired paths accurately. RNP extends the capabilities of modern airplane navigation systems by providing real-time estimates of navigation uncertainty, and some other features that facilitate the predictability of airplane navigation (Mohleji and Stevens, 2006). It also could facilitate closely-spaced parallel arrivals and departures in the terminal. A precise characterisation of airplane performance is key to designing more efficient airspace routes and procedures. Separation standards based on RNP capabilities afford Performance-Based Navigation (PBN) and 4D trajectory (4DTs) management concepts.

An appropriate management of arrival operations could alleviate congestion which impacts directly in capacity and efficiency of the overall ATM operations. A discrete event specification of aircraft trajectories could contribute to analyze the perturbations that affect different arrival operations. With a suitable decision support tool, it will be easy to accurately compute arrival schedules that are essential to obtain end-to-end benefits of RNP.

The present work develops an innovative strategic trajectory de-confliction algorithm able to manage TMA arrival operations by applying techniques such as Coloured Petri Nets (CPNs). A causal Discrete Event Simulation (DES) model seems a promising approach to improve TMA airspace capacity by generating conflict trajectories. Therefore, a conflict detection and resolution (CD&CR) algorithm is proposed to deal with arrivals aircraft's trajectories while providing efficient landing sequences which maximise air and runway capacity. The CD&CR algorithm is addressed as a centralised approach to reduce air traffic control (ATC) workload by using a decision support tool (DST).

CD&CR algorithms for 4D trajectories and their interactions in a TMA are essential to remove non-effective operations, avoid delay propagation between arrivals and optimise the occupancy of the runway. Aircraft CD&CR algorithms have a long history of investigation, but with emerging activity in the free flight policies, new technologies, and an increased emphasis on economic and market factors, CD&CR needs to be re-examined.

Conflict resolution consists in avoidance manoeuvres applied by the cooperative aircraft (leading or trailing aircraft). These manoeuvres can be heading angle changes (i.e., horizontal deviation), velocity changes, or vertical manoeuvres (flight level changes). In a landing sequence, for each aircraft concerned, it is assumed that a conflict-free trajectory has to be proposed by the automated, centralised decision support tool assisting the ATC. An aircraft is considered in conflict if there exists an instant when the vertical separation and/or the horizontal separation minima are lost. The separation criteria are defined by the - ICAO DOC 4444.

There are a variety of concepts in development that address the issue of reducing congestion and increasing operational efficiency. With regard to arrival operations, an efficient landing sequence will contribute to maintain the throughput as close as possible to the available runway capacity, ensuring optimisation of the airport manoeuvring area traffic flows and the minimisation of ground and airborne delay while conforming to the separation requirements. At the same time, it is expected that it will also enable the more widespread use of CDAs (Piera and Baruwa, 2008).

The aim of this work is to propose a discrete event model using CPNs for merging arrival flows in a conflict free landing sequence. The conflict resolution method proposes a set of conflict free trajectories found by applying certain manoeuvres to a given set of aircraft. Manoeuvres are performed in a non-cooperative scenario, i.e. only one of the aircraft involved in the conflict will change its nominal route. These manoeuvres can be heading angle changes (i.e. horizontal deviation), velocity changes, or vertical manoeuvres. It is assumed the use of FMS capable of RNAV, RNP, as well as Vertical Navigation (VNAV). Furthermore, it is assumed that the ATM automation system provides support to enable the airplane to fully utilise the above capabilities while maximising runway capacity.

In the last decades different researchers have been studying the evolution of air traffic and have been designing CD&CR tools to improve ATM performance. Most proposed solutions have been exercised through a set of scripted, controlled or simplified scenarios and algorithms are focused mainly in the en-route phase.

Many approaches for conflict resolution have been proposed for en-route and/or TMA sectors, although more emphasis is given to en-route sectors. In Kuchar and Yang (2000) a survey of 68 conflict detection and conflict resolution (CD&CR) modelling methods are presented. Some of these methods are currently in use or under operational evaluation; for example the user interface of TCAS (Harman, 1989) which provides resolution advisories (flight level changes) to pilots involved in two-aircraft conflicts; or Centre/TRACON Automation System (CTAS) which is a suite of air traffic decision support tools developed by NASA Ames Research Centre (Slattery and Green, 1994).

CD&CR have expanded to include different approaches such as; Genetic Algorithms for example, Mondoloni and Conway (2003), Vivona et al. (2005), Delahaye et al. (2010), among others; linear programming as in Pallottino et al. (2002); Stochastic Optimisation as in Vela et al. (2009), Ant Colony Optimisation from Duran (2009); among others and the incorporation of arrival-time for a better control of the arrival sequence (for example, Bilimoria and Lee, 2002 and Mondoloni and Ballin, 2001, among others).

Favennec et al. (2008, 2009) present the point merge technique which is an innovative technique to tackle the airspace congestion. It enables integrating flows in the terminal area through systematic procedures without relying on open loop radar vectoring. The principle is to achieve the aircraft sequence on a point (with conventional direct-to instructions) using predefined legs at iso-distance to this point for path shortening or path stretching. Except RNAV capabilities, no specific airborne functions or ground tools are required. More detail information can be obtain from Ivanescu et al. (2009a,b), Boursier et al. (2006) and Boursier et al. (2007).

This study presents a model based on similar assumption than the point merge: both approaches are based on a pre-defined route structure; and, trajectories are characterised by a sequence of waypoints some of which are shared between the different converging arrival trajectories representing merging points. It is also assumed that aircraft follow a nominal path or STAR to the airport destination.

As a brief outline of the rest of the paper, Section 3 describes the problem scenario and the different control actions to avoid conflicts while an overview of the proposed conflict detection and resolution algorithm. Section 3 describes the main aspects concerning CPNs algorithm. Section 4 provides the proposed model description while Section 5 gives the results. Finally conclusions are detailed.

3.2 Problem description: scenario and control actions

The present work was developed within the ATLANTIDA project. The ATLANTIDA project is a research effort in the air traffic management domain leaded by Boeing Research & Technology Europe (BR&TE) together with key research companies and Spanish universities, with the aim of providing a significant contribution to the attainment of the common European goals set by the SESAR program and beyond. Universitat Autònoma de Barcelona (UAB) has been collaborating with BR&TE, ATOS-Origin and INDRA in the development of a causal model to improve CD&CR algorithm's performance.

The proposed approach utilizes concepts based on a set of manoeuvres such as heading and speed changes for conflict resolution problems in TMA at tactical level. This manoeuvres must be performed in a Medium Term time window, time typically required for an aircraft to traverse an air traffic control sector, and any additional time in which would be beneficial for planning ahead for future aircraft(normally between 15-45 minutes). These types of manoeuvres are routinely used in current Air Traffic Control practice since they are easily understandable by pilots as well as easily implementable by on-board autopilots which regulate the aircraft to heading and speed waypoints. In a Medium Term time window, conflict scenarios can be smoothly resolved so that they do not become near-range threats.

The operational context of the proposed causal model assumes that aircraft is fully equipped and therefore, the proposed conflict free trajectories can be executed perfectly and that neither data-link transmission delays, nor pilot-action delays are presented. It takes for granted that aircraft are able to fly at the highest and lowest permissible speeds over each flight link and within a fixed altitude layer until the Top of Descend (TOD). The model does not take into account the time to execute state changes; nor uncertainties in the estimation of aircraft position or unexpected wind fields. It is assumed that deviations are small, and the time to complete any manoeuvre change is small in comparison to the time until conflict. The arrival traffic sequence is assumed to have been determined upstream in the TMA by an arrival manager (AMAN) or in a First-Come-First-Served (FCFS) policy and is conflict free when entering at TMA.

In the proposed CD&CR algorithm, each aircraft has attached a set of "*waypoint time stamp*" which represents the expected passing time of an aircraft by/over that waypoint (four dimension waypoints). A given conflict free predefined sequence of aircraft is feed to TMA through different arrival entries upon on a single runway airport.

A synthetic STAR configuration of the Gran Canaria TMA has been used (as depicted in Figure 2-1) to test the benefits of the proposed algorithm. In the arrival phase, three routes fuse into one single route, by merging in two different waypoints. Three different routes were defined, two correspond to current STARs defined in the Spanish Aeronautical Information Publication (AIP), TERTO3C and RUSIK3C, and one additional STAR was defined in order to complicate the traffic flow in the scenario presented. This last STAR is defined by the name NPWT3C. The waypoints sequence for each of the three STARs is as follows:

- TERTO3C: TERTO, LZR, BETAN, CANIS, ENETA (IAF), LPC (FAF), RWY
- RUSIK3C: RUSIK, FTV, FAYTA, CANIS, ENETA (IAF), LPC (FAF), RWY
- NWPT3C:NWPT, FAYTA, CANIS, ENETA (IAF), LPC (FAF), RWY

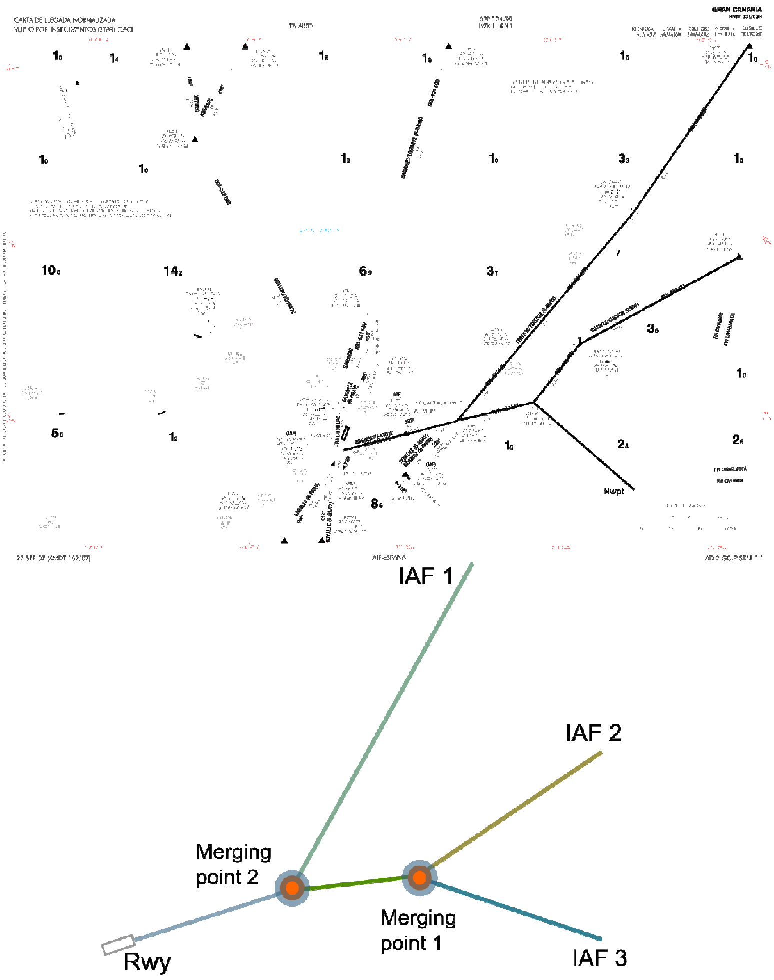

Figure 3-1: Gran Canaria STAR configuration.

For simplicity, the STAR configuration is represented by the proposed route network shown in Figure 3-1The different merging waypoints called; merging point 1 at FAYTA (merging of routes RUSIK3C and NWPT3C); and merging point 2 at CANIS waypoint (merging of routes TERTO3C, NWPT3C and RUSIK3C). Aircraft trajectories have attached information about location in time and space of each representative waypoint (express as 4D waypoints i.e. 3DT's+time) in the route to be flown.

3.2.1 METHODOLOGY AND CONTROL ACTIONS DESCRIPTION

Conflict-free trajectories are achieve by spacing appropriately the route converging to runway either by changing trajectory but maintaining speed profile; or by changing trajectory and speed profile of the aircraft. As a consequence, the algorithm re-calculates the expected arrival time of each aircraft when entering TMA in order to feed FMS with conflict-free trajectories. The selection of an appropriate control action depends on the information of the traffic situation. Figure 3-2 summarizes the different control actions implemented into the model.

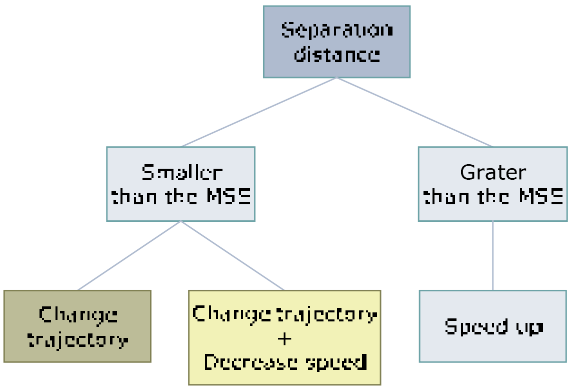

Figure 3-2: Control actions.

An estimation of the longitudinal time separation between consecutive aircraft when passing by/though the merging points is done by comparing the expected passing time of an aircraft through/by each merging point, i.e.;

$$SD = x3 - y3 \qquad \textbf{Ec. 1}$$

Where: *SD* is the estimated longitudinal time separation distance between two expected arrival time aircraft,

x3 is the expected passing time of the leading aircraft, and

y3 is the expected passing time of the trailing aircraft.

After the algorithm estimates the longitudinal separation SD, it is compared with the minimum separation standard (MSS) which is the minimum wake vortex separation standard defined by the Air Traffic Management – ICAO DOC 4444. These separation distances are expressed in terms of a time-based separation criterion and must take into account the characteristics of each aircraft (type, weight, speed, altitude). As Figure 3-2 suggests, when:

$$SD \leq MSS \quad \textbf{Ec. 2}$$

a conflict is detected and a control action must be performed to ensure a proper longitudinal separation distance. The algorithm considers two different control actions for this situation as in the work of (Pallottino2002):

- *Path shortening/Path stretching technique:* Aircraft fly at the same speed and it is only allowed to change instantaneously the direction of flight. This case is also called the heading angle change problem (HAC problem);
- *Speed regulations;* Aircraft is allowed to change speed but the direction of flight remains fixed. This is also called the Velocity Change problem (VC problem).
- *Speed regulations + Path shortening/Path stretching technique:* The combination of both actions; to change speed and the direction of flight.

On the other hand, when:

$$SD > MSS \quad \text{Ec. 3}$$

There is no conflict and latent capacity could be absorbed by a speed up manoeuvre.

3.2.2 PATH SHORTENING/PATH STRETCHING TECHNIQUE

The objective of this technique is to enlarge/shorten the distance to be flown from the TMA entry point until the last merging point in the route in a manner that aircraft avoid conflicts maintaining its original speed profile. To enlarge distance, aircraft must deviate from its original trajectory, changing its direction instantaneously.

As a result, a delay Δt is applied to the original trajectory to avoid conflicts which can also be seen as a delay compensated solution. It avoids the conflict using a heading change and if necessary by combining heading change with a decrement of speed in such a way that the delay introduced by the path stretching technique generates a new trajectory which avoids the conflict.

The delay Δt (in time) needed to avoid conflicts is calculated by comparing the separation distance between the leading and following aircraft SD to the MSS in the last merging point, i.e.

$$\Delta t = |MSS - SD| \quad \textbf{Ec. 4}$$

When a conflict is detected in the original route, the trailing aircraft changes its direction until a certain “turning point” where the aircraft is redirected towards the original route. Manoeuvres are assumed to start when passing by/though the TMA entry point and finishing at the merging point. The manoeuvres to generate the alternative trajectories in a segment are schematized on Figure 3-4. These proposed manoeuvres are called turning point manoeuvres and offset manoeuvres by most of the literature.

The geometry of the turning point manoeuvre is similar to a triangle with bended corners while the offset manoeuvre is more similar than a trapezium shape with bended corners. Each segment defined by two fix waypoint is allowed to have an alternative trajectory that is used if a delay compensation should be applied. Turns, which result from a degree of bank of approximately 45°, are the only ones allowed due to operational reasons.

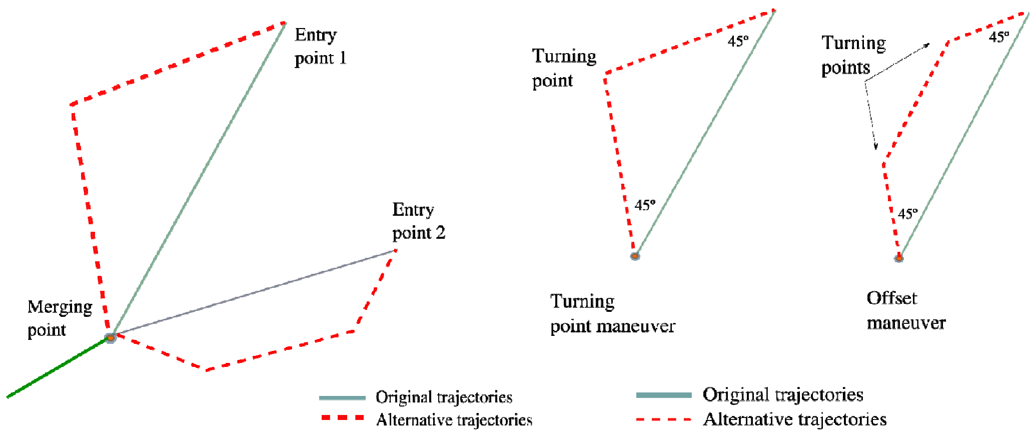

Figure 3-3: Three trajectories with two merging points.

The utilization of this technique is an important similarity between our approach and Point Merge techniques since conflict resolution strategy relies on the introduction of a pre-defined route structure consisting of merge points and segments called “legs” to stretch/short distance to be flown. So the DST should compute only the right turning points.

3.2.3 SPEED REGULATIONS

Speed regulation manoeuvres can be presented in two different forms, either to accelerate an aircraft or to des-accelerate it. Each manoeuvre has a particular objective: if the speed regulation is a des-acceleration manoeuvre, then a delay is applied to the original time stamp passing time by/over waypoints, while the aim of the acceleration manoeuvre is to reduce the time to be flown which can be use to compensate another delay induced by a path change. It is important to keep in mind that in any case, a safety distance must be preserved.

3.2.4 SPEED REGULATIONS + PATH SHORTENING/PATH STRETCHING TECHNIQUE

The objective of this technique is to decrease speed of the aircraft at the same time than the distance to be flown is augmented. This alternative control action will only be applied when the delay obtained through the stretching technique cannot solve the conflict detected at the merging point, and an extra delay is required.

3.3 Coloured Petri Net approach

CPN is a high level modelling formalism for complex systems which have been widely used to model and verify systems, allowing representing not only the system's dynamic and static behaviour but also the information flow.

The main CPN components that fulfil the modelling requirements are:

- Places: They are very useful to specify both queues and logical conditions. Graphically represented by circles.
- Transitions: They represent the events of the system. Graphically represented by rectangles.
- Input Arc Expressions and Guards: Are used to indicate which type of tokens can be used to fire a transition.
- Output Arc Expressions: Are used to indicate the system state change that appears as a result of firing a transition.
- Colour Sets: Determines the types, operations and functions that can be used by the elements of the CPN model. Token colours can be seen as entity attributes of commercial simulation software packages.
- State Vector: The smallest information needed to predict the events that can appear. The state vector represents the number of tokens in each place, and the colours of each token.

The Colour sets will allow the modeller to specify the entity attributes. The output arc expressions allow to define which actions should be coded in the event routines associated with each event (transition). The input arc expressions will allow specifying the event pre-conditions. The state vector will allow the modeller to understand when and why an event can appear, and consequently to introduce new pre-conditions (or remove them) in the model, or change some variable or attribute values in the event routines to disable active events.

From the Operational Research (OR) point of view, the CPN model provides the following mathematical structures:

- Variables: A variable can be identified for each colour specified in every place node.
- Domains: The domains of the variables can be easily determined by enumerating all the tokens specified in the initial state.
- Constraints: Can be obtained straightforward from the arc and guard expressions. Arc expressions can contain constant values, colour variables or mathematical expressions.

From the Artificial Intelligence (AI) point of view, the coverability tree of a CPN model allows to determine:

- All the events that could appear according to a particular system state (Figure 3-5).
- All the events that can set off the firing of a particular event.
- All the system states (markings) that can be reached starting from a certain initial system operating conditions M0.

The transition sequence to be fired to drive the system from a certain initial state to a desired end-state.

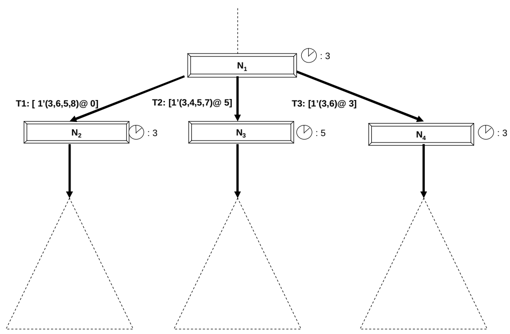

Figure 3-4: Example of a coverability tree

Different approaches have been developed to combine the high description capabilities of simulation models with the benefits of analytical techniques of optimization models that have been proposed in several simulation–optimization approaches. One of the most classical and widely accepted has been the parameterization of the decision variables of the simulation model in such a way that an optimization algorithm can efficiently check the results of the most promising decision variable values. At the end of the procedure it compares the different system outputs and keeps the best of the solutions obtained (Mujica, 2010).

3.4 Model description

The medium term CD&CR model proposed has been specified in the CPN formalism. The discrete event approach has been specified using seven colours, five places and nine transitions. This model can be integrated with the AMAN/DMAN CPN model (Piera, 2008) to optimize a shared mode runway in which the best landing sequence can also be computed.

As described in section 2, three different control actions can take place in the scenario described in Figure 3-3. Indeed, let us consider these control actions as events which are represented by three different blocks of transitions in our CPN model.

- The first block contains four transitions which derivates from the event of "*Change trajectory*"; this event takes place when a conflict between two aircraft is detected in a merging point. Taking into account the scenario presented in Figure 3-2, three transitions derivate from this event: Change trajectory from TERTO to merging point 2, change trajectory from RUSIK to merging point 2 and finally change trajectory from NWPT to merging point 2.

- The second block contains three transitions which are obtained from the event "*Change trajectory + Decrease speed*" which takes place when a conflict between two aircraft is detected in a merging point and cannot be solved only by a vectorisation procedure. Therefore, taking into account the scenario presented in Figure 3-2, three transitions derivate from this event: reduce speed from TERTO to merging point 2, reduce speed from RUSIK to merging point 2 and finally reduce speed from NWPT to merging point 2.

- The third block computes for the acceleration event which takes place when the separation distance between the leading and the trailing aircraft is greater than MSS. In order to acquire a reduction of time from the TMA entry point to the merging point the trailing aircraft is accelerated until an optimal or best separations distance (in time) is reached. Another transition is used to compute the speed profile along the new trajectory so no extra speed changes will be required.

- Finally, two more transitions are required to model the conflict detection phase, one per each merging point.

3.4.1 NET SPECIFICATION & DESCRIPTION

The model does not take into account the time needed to execute state changes. It is assumed that deviations are small, and the time to complete any manoeuvre change is small in comparison to duration of conflict. The arrival traffic sequence is assumed to have been determined upstream; therefore sequencing is implicitly defined in the traffic preparation input file.

Table 1 summarizes the colours used to describe all the information required in the places to define the aircraft trajectory in 4D.

Table 3-1: Colour specification

Colour	Meaning
aid	Aircraft identification
idp	Waypoint identification
t	Time
vel	Average speed
de	Distance between two waypoints
c	Control variables
wp	Waypoint information

Table 3-2: Place specification

Place	Colour	Definition
Segments	S	aid*wp*wp*t*v*wp*t*de
G	G	c,c,c
Solution	R	aid,wp,v,de
Pair	P	aid, aid,t,wp,wp

In the CPN representation, the place called "*Segments*" takes into account the following information regarding each aircraft trajectory (corresponding to different colour attributes): Colour *aid* corresponds to the aircraft identification in a trajectory; colour variable *idp1* corresponds to the STAR of each route while the *idp2* keeps the information regarding to the passing waypoint identification; colour *t* and *vel* represents its corresponding current time and speed profile. The third *idp* colour corresponds to the next waypoint identification of the trajectory while second colour *t* has information about STAR entry time. Finally the *t* and *de* colour corresponds to STAR entry time and distance, respectively. Place specifications are shown in Table 2 and detailed as follows:

Place "*G*" considers only three colours; The first colour (i.e. *d10)* is *0* only when the pair of consecutive aircraft considered has not been previously evaluated or has not already been forced to change their speed in order to avoid conflicts. That same colour is equal to *2* when the pair of aircraft has to be evaluated in merging point 1 after a vectorisation (path stretching) has been proposed. Finally, colour *d10* is set to *3* when the pair of aircraft has to be evaluated in merging point 2 after a speed-up control action has been applied. Colour *c3* and *c4* are control variables that indicate the number of the following aircraft to be evaluated in FAYTA and CANIS, respectively. Therefore, if the transition concerns FAYTA, colour *c3* will be incremented in one unit to update the next pair to be evaluated in this waypoint.

Place "*Solutions*" stores the information regarding whether the conflict has been successfully solved or not and also the aircraft involved in the solution. This node contains the aircraft identification, its corresponding passing time, medium speed and distance to be flown.

Place "*Pair*" contains the information that links the leading and the trailing aircraft ('x1' and 'y1', respectively) with the next passing time (x11) of aircraft 'y' and a control variable (c3 or c4) that indicates the trailing aircraft to be evaluated in FAYTA or CANIS. After firing this transition, the information is properly updated in all place nodes since the vectorisation has been completed.

3.4.2 EVENT SPECIFICATION EXAMPLE

To show how the proposed CPN model works, one of the ten transitions is explained. Figure 3-5 illustrates the speed up event. For this transition four places have been used:

a) Place *Segments* which is the one in charge for the speed modification. It chooses a pair of aircraft in the sequence (e.g. *x1* & *y1*) with its corresponding information attached (see Table 2). After executing the event some changes are applied to each aircraft, for example colour *z3* that represents passing time by merge point 2 changes to a new value: $z3 = x3 + 120$ which means that new passing time of the trailing aircraft has been assigned 120 [s] after the passing time of the leading aircraft *(x3);* colour *z4* (speed profile) has also a new value: $divv(aa64,(x3+120-y12))$ which becomes the new speed of the trailing aircraft from TERTO to merge point 2. This new speed is computed based on the trailing: first of all, aircraft are assumed to fly maximum trajectory (*aa64*) and finally the trailing aircraft must fly 120 [s] after the leading aircraft in the same merging point, been 120[s] the MSS for the types of aircraft involved in the resolution.

b) Place *Pair* takes the same pair of aircraft that node *Segments* (*x1* & *y1*), with its corresponding attached information. This place is used as a control mechanism of the model. Colour *c4* is another control variable that indicates the sequence of the trailing aircraft, and finally $c3=4$ indicates which merging point is been evaluated.

c) Place *G* indicates if an aircraft needs to be re-evaluated (denoted when colour *d10 takes value 0)* colours *c3 and c4* are linked to node *Pair* as control variables.

d) Place *Solution* stores only information regarding the leading aircraft (note that this aircraft will not have conflict with any other aircraft because it has been previously solved). Node G will increase colour value *c4* in one unit to specify that the trailing aircraft should be evaluated; if the trailing aircraft comes from RUSIK or NWPT, $d10=3$ to indicate that this aircraft has to be re-evaluated in the other merging point to ensure conflict free trajectories.

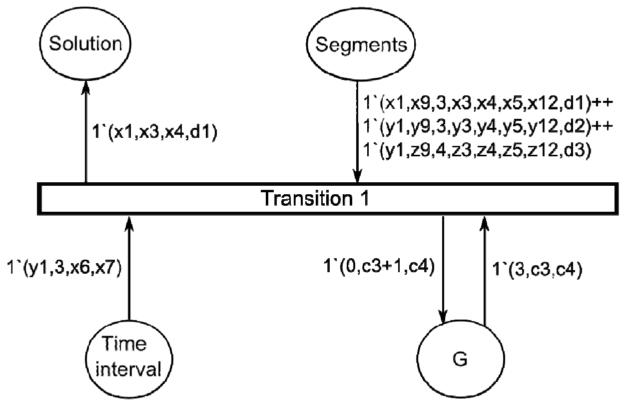

Figure 3-5: Example of the CPN for the CD&CR algorithm.

3.5 *Results*

At a busy traffic period, the arriving traffic flow at Gran Canaria's airport is usually between 20 to 30 aircraft per hour. The arrival traffic sequence is conflict-free when entering TMA and is assumed to have been determined in an input file by the AMAN.

To test the performance of the proposed CD&CR CPN model different synthetic traffic scenarios have been designed and implemented. Table 3 illustrates a 4DT specification of a 20 aircraft scenario arriving to Gran Canaria TMA.

Table 3-3: 20 aircraft scenario data

Aircraft id	TMA entry point	TMA entry time [s]	WPT TAS [Kts]	Mach	FL	WPT name	WPT time [s]	WPT TAS [Kts]	FL	WPT name	WPT time [s]	WPT TAS [Kts]	FL	WPT name	WPT time [s]	WPT TAS [Kts]	FL	WPT name	WPT time [s]	WPT TAS [Kts]	FL
B737 ATLS9001	RUSIK	260	466	0,79	300	FTV	740	466	300	FAYTA	920	466	300	CANIS	1160	408	136	ENETA	1820	191,19	136
B737 ATLS9002	TERTO	300	466	0,79	300	LZR	840	466	300	BETAN	1320	466	300	CANIS	1560	409	136	ENETA	2280	196,05	136
B737 ATLS9003	TERTO	490	466	0,79	300	LZR	1030	466	300	BETAN	1510	466	300	CANIS	1730	408	136	ENETA	2470	197,55	136
B773 ATLS9004	NWPT	870	466	0,74	300		1410	466	300	FAYTA	1890	466	300	CANIS	2130	408	136	ENETA	2850	188,52	136
B737 ATLS9005	RUSIK	870	466	0,79	300	FTV	1350	466	300	FAYTA	1530	466	300	CANIS	1770	408	136	ENETA	2430	181,41	136
B737 ATLS9006	RUSIK	1040	466	0,79	300	FTV	1520	466	300	FAYTA	1700	466	300	CANIS	1940	408	136	ENETA	2600	196,05	136
B737 ATLS9007	TERTO	1160	466	0,79	300	LZR	1700	466	300	BETAN	2180	466	300	CANIS	2420	409	136	ENETA	3140	218,67	136
B737 ATLS9008	RUSIK	1200	466	0,79	300	FTV	1680	466	300	FAYTA	1860	466	300	CANIS	2100	408	136	ENETA	2760	197,55	136
B737 ATLS9009	TERTO	1300	466	0,79	300	LZR	1840	466	300	BETAN	2320	466	300	CANIS	2560	409	136	ENETA	3280	218,67	136
B773 ATLS9010	NWPT	1570	466	0,74	300		2110	466	300	FAYTA	2590	466	300	CANIS	2830	408	136	ENETA	3550	188,52	136
B737 ATLS9011	TERTO	1980	466	0,79	300	LZR	2520	466	300	BETAN	3000	466	300	CANIS	3240	409	136	ENETA	3960	197,55	136
B773 ATLS9012	NWPT	2060	466	0,74	300		2600	466	300	FAYTA	3080	466	300	CANIS	3320	408	136	ENETA	4040	196,05	136
B737 ATLS9013	TERTO	2250	466	0,79	300	LZR	2790	466	300	BETAN	3270	466	300	CANIS	3510	409	136	ENETA	4230	196,05	136
B737 ATLS9014	RUSIK	2450	466	0,79	300	FTV	2930	466	300	FAYTA	3110	466	300	CANIS	3350	408	136	ENETA	4010	181,41	136
B737 ATLS9015	RUSIK	2690	466	0,79	300	FTV	3170	466	300	FAYTA	3350	466	300	CANIS	3590	408	136	ENETA	4250	218,67	136
B737 ATLS9016	TERTO	2800	466	0,79	300	LZR	3340	466	300	BETAN	3820	466	300	CANIS	4060	409	136	ENETA	4780	197,55	136
B737 ATLS9017	TERTO	3000	466	0,79	300	LZR	3540	466	300	BETAN	4020	466	300	CANIS	4260	409	136	ENETA	4980	218,67	136
B737 ATLS9018	TERTO	3220	466	0,79	300	LZR	3760	466	300	BETAN	4240	466	300	CANIS	4480	409	136	ENETA	5200	196,05	136
B773 ATLS9019	NWPT	3260	466	0,74	300		3800	466	300	FAYTA	4280	466	300	CANIS	4320	408	136	ENETA	5240	188,52	136
B737 ATLS9020	RUSIK	3370	466	0,79	300	FTV	3850	466	300	FAYTA	4030	466	300	CANIS	4270	408	136	ENETA	4930	197,55	136

The model has found conflict free trajectories for this scenario and two of this trajectories, have been chosen to be validated in a Boeing 737-800 simulator, using both the real-time simulator, and the FMS onboard.

A summary of nominal initial data regarding the selected trajectories, RUSIK3C and TERTO3C, can be found in Table 4 and Table 5, respectively. In both cases, a conflict has been detected in CANIS when following the nominal STAR, so a delay has been calculated by the CR algorithm and a new trajectory has been generated ensuring minimum change of vertical and speed profiles. As a consequence, the Estimated Time of Arrival (ETA) has also been modified, for this particular case; a 2minute delay has been calculated. Notice that time in the FMS is given in minutes, although the CD&R algorithm works with precision of seconds.

Table 3-4: Summary of nominal data for RUSIK3C

Waypoint	Latitude		Longitude		FL	Distance (NM)	IAS (Kts)	TAS (Kts)	Abas.tiem (HHMM)	Rel.time (min)
RUSIK	28º	54.4’	-12º	49.0’	300	0	300	466	1512	0
FTV	28º	25.8’	-13º	51.9’	300	62	300	466	1520	8
FAYTA	28º	06.5’	-14º	08.3’	300	24	300	466	1523	11
CANIS	28º	00.0’	-14º	38.9’	213	28	300	408	1527	15
ENETA	27º	55.0’	-14º	49.0’	136	19	300	364	1530	18

Table 3-5: Summary of nominal data for TERTO3C

Waypoint	Latitude		Longitude		FL	Distance (NM)	IAS (Kts)	TAS (Kts)	Abas.tiem (HHMM)	Rel.time (min)
TERTO	30º	06.3’	-12º	43.0’	300	0	300	466	1451	0
LZR	29º	10.0’	-13º	30.6’	300	70	300	466	1500	9
BETAN	28º	24.6’	-14º	15.1’	300	60	300	466	1508	17
CANIS	28º	00.0’	-14º	38.9’	214	32	300	409	1512	21
ENETA	27º	55.0’	-14º	59.0’	136	19	300	364	1515	24

For the purpose of this document, the initial information to feed the Boeing 737-800 simulator is presented in Table 6. For simplification, trajectories have been considered only up to ENETA. Beyond this waypoint, all the vertical and speed profiles are considered to be identical. It should be pointed out, that in absence of wind the TAS speed can also be considered as Ground Speed.

Table 3-6:aircraft scenario

Aircraft model	B787-800
Wind:	No wind
Weight	52.000 Kg
Entry Flight Level	FL300
Entry mach	0.79 (300KIAS)

The nominal RUSIK3C STAR with its corresponding waypoints up to ENETA is presented in Table 4 and depicted in Figure 3-6. Times of the Figures are in format HHMM and the initial time corresponds to the internal time used by the simulator. Thus, it has been taken the relative values of these times considering the TMA entry time first value as t=0.

Table 3-7:Summary of FMS data for CR-modified RUSIK3C

Waypoint	Latitude		Longitude		FL	Distance (NM)	IAS (Kts)	TAS (Kts)	Abas.tiem (HHMM)	Rel.time (min)
RUSIK	28º	54.4’	-12º	49.0’	300	0	300	466	1621	0
WPT66	27º	57.9’	-13º	25.4’	300	64	300	466	1629	8
CANIS	28º	00.0’	-14º	38.9’	214	64	300	409	1638	17
ENETA	27º	55.0’	-14º	59.6’	136	19	300	364	1641	20

Figure 3-6: RUSIC3C Nominal STAR route.

Figure 3-7 and Figure 3-8 show part of the FMS simulator navigational instrumentation where some of the initial conditions are presented (information of Table 6 can also be found). For instance, in Figure 3-7 provides the STAR waypoints information with its corresponding flight level, speed (in Mach or in KIAS, depending on the flight level), heading between each pair of waypoints, and the distances between each pair of waypoints (with precision of nautical miles). Notice that waypoints after ENETA have not been considered in this experiment since all the processed trajectories followed exactly the same descent profile from ENETA to runway. In addition, waypoint TOD12 has also been omitted since it is neither a part of this experiment, nor of the nominal RUSIK STAR (the omission of this waypoint has no effects in the results of this experiment). Figure 3-8 depicts the associated Expected Time of Arrival (ETA) calculated by the FMS and absence of wind conditions. The time format is given in HHMM. g

Figure 3-7: RUSIC3C Nominal FMS data

Figure 3-8: RUSIC3C Estimated Time of Arrival and wind conditions for Nominal route;

After applying the CD&CR CPN algorithm a new trajectory is generated, see Figure 3-9. The new route starts in RUSIK but instead of following the nominal STAR, it is deviated from waypoints RUSIK passing by WPT66 and recovering it original route in CANIS.

Figure 3-9: RUSIC3C of a trajectory in conflict

Figure 3-10 illustrates some of the FMS simulator navigational instrumentation after applying the CR algorithm. The modified data showed corresponds to speed, flight level, heading, distance and its associated ETAs to each of the waypoints.

Figure 3-10: Modified conditions for route RUSIC3C;

As for the RUSIK3C aircraft trajectory presented in Table 5, a TERTO3C trajectory has been validated in the Boeing 737-800 simulator (see Figure 3-11). The TERTO3C nominal trajectory is depicted in Figure 3-12 where part of the FMS simulator navigational instrumentation with the initial conditions is presented.

Figure 3-11: TERTO3C Nominal STAR route.

The resulting trajectory of the CR algorithm is shown in Table 8 and depicted in Figure 3-13; it provides aircraft information with its corresponding flight level, speed profile, heading and distance between each pair of waypoints (with precision of nautical miles).

Table 3-8: Summary of CR-modified data for CR-modified data for TERTO3C

Waypoint	Latitude		Longitude		FL	Distance (NM)	IAS (Kts)	TAS (Kts)	Abas.tiem (HHMM)	Rel.time (min)
TERTO	30º	06.3’	-12º	43.0’	300	0	300	466	1451	0
WPT55	29º	31.7’’	-14º	21.9’	300	92	300	466	1623	9
CANIS	28º	00.0’	-14º	38.9’	214	32	300	409	1512	21
ENETA	27º	55.0’	-14º	59.0’	136	19	300	364	1515	24

Figure 3-12: TERTO3C Nominal FMS data

Figure 3-13: Modified TERTO3C of a trajectory in conflict

Figure 3-14 show the waypoints of the new route generated by CR to solve a conflict in CANIS. The aircraft enter TMA by TERTO and then deviates from the STAR until a new waypoint called WPT55 where the aircraft heads back to CANIS to recover its original route towards ENETA.

Figure 3-14: Modified conditions for route TERTO3C;

As stated in the introduction, the proposed model applies the path shortening/ path stretching technique as in the PM. The two configurations of the same airspace system are depicted in Figure 3-15: one for the Point Merge technique (right hand side) and the other for the proposed approach (left hand side). In both approaches, the system configuration consists of two entry points and a single merge waypoint.

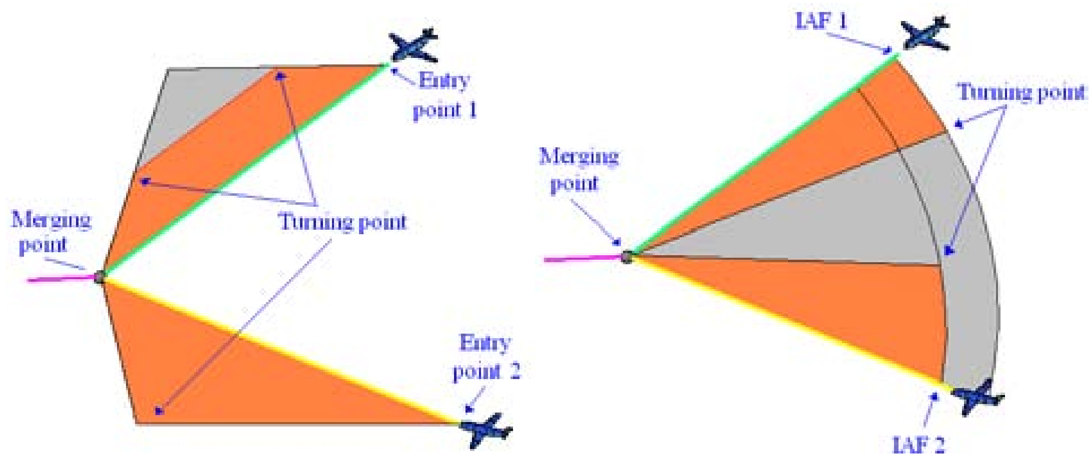

Figure 3-15: Example of new trajectory with turning point.

The PM technique is a structured technique that aims to improve, harmonise and standardise arrival operations in the terminal area with existing technology. The principle is to achieve an aircraft sequence on a point (with conventional direct-to instructions) using predefined legs at iso-distance to this point for path shortening or path stretching. Figure 3-7 (right hand side) depicts the denoted Point Merge System, the merge point and its corresponding sequencing legs (Ivanescu, 2009a).

In Favennec, 2009 the point merge procedure was studied and found feasible and beneficial in various 'generic' environments in Approach, notably with two, three or four entry points; one or two runways; and different TMA sizes. Two different route structures to integrate multiple Point Merge systems are studied in the same work. The one where each system could include one merge point, and all would have a common exit point (called *parallel* route structure); and the one depicted in Figure 3-1, which could design successive PM systems in the route structure (called *serial* route structure).

When dealing with parallel route structures with different arrival flows to be merged through multiple entry points, PM would require a large number of flight levels to be used in total, and/or larger distances between the legs and the merge point to allow space for descent, and possibly a smaller distance between the sequencing legs to ensure that the equidistance requirement has been adhered to. Another solution to deal with these configurations may be to combine PM systems (serial configuration). Using this approach, specific constraints can be considered, or the use of the PM technique with a split between E-TMA/TMA can also be introduced into this approach. However, such configurations have not been tested yet and are subject of further research.

In the proposed approach two merge points have been combined and are treated as serial point merge systems, taking into account all arrival flows while ensuring a spacing criteria.

Vertical profile has not been modified, i.e. it is intended to follow the same Flight level unless there is a conflict while in the PM more than two levels are used by the sequencing legs may also become an issue in the availability of spare levels. Furthermore, the proposed model has been tested using three different STARs and two merging points, providing excellent results for a traffic peak. In fact, the causal CPN model could be extended to different number of STARs and merging point configurations, while multiple point merge systems require the analysis of particular solutions to evaluate the cause effect configuration. The analysis of the causalities that appear as outstream interactions between other serial configurations using the CPN formalism is part of ongoing research.

3.6 Conclusions

A CD&CR algorithm for multi-aircraft using a discrete event approach in the CPN formalism has been proposed. A case study with 20 arrival aircraft has been successfully solved. And two of these trajectories have been validated by Boeing 737-800 simulator, using both the real-time simulator, and the FMS onboard, proving to be flyable.

The CD&CR algorithm computes the future passing times, speed and positions of each aircraft according to certain characteristics. The safety distance requirements due to vortex turbulences at merging points are considered as constraints in order to properly solve the problem. The solution is obtained using the coverability tree associated to the CPN. Feasible 4DT conflict free trajectories have been generated using computer simulation. The model scope can be extended to incorporate economic variables as for example fuel consumption aspects (BADA referenced). When incorporating these variables, it is possible to design a cost function that would be minimized by using an algorithm that explores the coverability tree associated with the model.

One of the key-point of such a design is the use of the state space to understand the behaviour of the model. Furthermore, the model has been designed in order to help the modeller to design new procedures to solve problems regarding future free flight concept.

The algorithms developed in this work fall in the kind of techniques of the first group, but the implementations presented in the last article can be further improved so that they can fall in the 3rd group of algorithms, but further research must be performed in order to develop algorithms that use the compact state space and are able to throw away information to avoid saturation of computer resources.

3.7 References

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3.8 Glossary

4DT's: four dimension trajectories

AMAN: arrival manager

ATC: air traffic controller

ATM: air traffic management

CD: conflict detection

CD&CR: conflict detection and resolution

CDA: Continuous Descent Approaches

CPN: Coloured Petri Net

CR: conflict resolution

CTAS: Center-TRACON Automation System

DES: Discrete Event System

DSTs: decision support tools

E-TMA: Extended TMA

FCFS: First-Come-First-Served

FMS: Flight Management System

MSS: wake vortex separation minimum separation standard

MTCD: Medium Term Conflict Detection

OR: Operational Research

PBN: Performance-Based Navigation

PM: point merge

RNAV: Area Navigation

RNP: Required Navigation Performance.

4 REVISITIZING THE PALLET LOADING PROBLEM USING A DISCRETE EVENT SYSTEM APPROACH TO MINIMIZE LOGISTIC COSTS

Abstract

This paper presents a new challenging modelling approach to support different heuristics to tackle the Pallet Loading Problem (PLP). A discrete event system model to tackle the PLP, is specified using the Coloured Petri Net formalism in order to integrate the model with the industrial context in which the PLP must be solved. New events can be formalized in the model to implement different heuristics to consider the upstream (production) and downstream (transport) influence of the palletizing activity in the logistic flow. A state space analysis is performed to evaluate the different solutions to fit the maximum number of boxes on a rectangular pallet, supporting the inherent box diversity (heterogeneous palletizing problems) of present production and distribution logistic systems. The heuristics implemented show that acceptable occupancy results can be obtained without requiring the exhaustive evaluation of the different feasible combination. The results demonstrate that it outperforms other approaches which have been suggested for this type of problem. Potentially useful extensions of the work are discussed.

4.1 Introduction

Palletizing has become an important issue not only in the transportation industry, but also a very important piece in the Supply Chain Management due to upstream and downstream influence in the logistics flow Curcio and Longo (2009), Tiacci, and Saetta (2009). It is well known that pallets filled in an optimal way reduce transportation and warehousing costs among others. Nevertheless, there are some hidden costs in which usually the palletizing plays a key role. The palletization of different box sizes in high diversity production systems and distribution centres force sometimes to accumulate a high quantity of boxes of the same type to optimize the pallet volume while unnecessarily increasing the lead time. Due to fierce cost competitivity, the palletizing should be seen also as an important link in all those logistics area where orders from customers must be prepared, placing the packages on pallets in an optimal way for the issue. A pallet filled in optimal conditions considers different aspects such as time spent in the process, stability and space utilization which is defined to be the percentage of pallet space or volume occupied by the load products. It is easy to note that a higher space utilization factor requires a smaller number of pallets; hence, a higher efficiency in the palletizing is obtained. Recent issues in transportation and storage costs have highlighted the importance of an optimal palletization, both in transit and in the warehouse. Transportation and warehouse costs are directly related to the type and number of pallets used for a shipment, which, in turn, is directly linked to proper space utilization, therefore an optimal filling of a pallet reduces the shipment costs as well as increases the stability and support of the load. A review of classical PLP approaches that focus on the manufacturer problem which regularly transports large quantities of a reduced set of master box types can be found in George and Robinson (1980), Bischoff and Dowsland (1982), Han et al. (1989), Ivancic et al. (1989), Gehring et al. (1990), Abdou and Yang (1994), Chua et al. (1998), Alvarez-Valdes et al. (2005), Lim et al. (2005), and Bischoff (2006).

Most of these classical packing strategies are based on the wall building approach presented by George and Robinson (1980), with some adaptations such as Bischoff and Dowsland (1982), Gehring et al. (1990), Schnell et al. (1997), and Bischoff (2006), among others. The wall building approach is a heuristic that loads the pallet with columns of boxes; each column is composed of a set of boxes stacked vertically and the column stacks are no higher than the maximum allowable pallet height (Abdou and Elmasry 1999). This method itself is a greedy heuristic which can lead to weak final solutions (Dowsland 1991). Other methods using spatial representation presented by Ngoi et al. (1994), and Chua et al. (1998) reduce the problem to a maximum set problem or an integer programming problem. For methods based on the spatial representation such as the one presented by Han et al. (1989), empty volume search routines are used to generate small spaces, whereas the successful utilisation of these small spaces is difficult.

For methods based on graph theory and integer programming (Ivancic et al. 1989), some disadvantages appear due to model simplification aspects and the inherent difficulty of the combinatorial nature of these problems. Some approaches to tackle the PLP such as Alvarez-Valdes et al. (2005), and Martins and Dell (2008), assume that all boxes have identical rectangular dimensions. On the whole, published works generally give successful implementations to solve particular PLP and provide some interesting insights into the various views on how successful packing can be best achieved (Lim et al 2005).

Even though these studies present feasible solutions for the cargo problem, there are a considerable number of scenarios which have received only fairly limited attention so far, and very poor solutions are obtained when classical algorithms are applied. An example of such scenarios is the loading patterns which are restricted to either layered or stacking columns. In previous studies, bins or containers are also considered as large regular-shaped rectangular boxes which can be loaded by vertical layers (stacking columns) and boxes are supported by its walls. This may be true when the study is focused on filling containers but the loading pattern in the pallet must be different because of the role that stability plays. In layered type models, the main disadvantage is that boxes must have identical height.

Maybe, though, the most relevant scenario appears when the cargo to be palletised consists of heterogeneous boxes (different dimensions), which is the opposite of the manufactures' problem because the empty space generated by the previously loaded boxes is so hard to treat. Distributors' centres are a particular case of this scenario, characterised by a high diversity of box types where items of varying sizes – representing an order from a customer – have to be loaded onto a pallet and delivered in different destinations in a predefined sequence.

In Abdou and ElMasry (1999), a challenging approach to reuse rectangular shaped three-dimensional empty space found anywhere at any given time on a pallet is presented, which is quite similar to free space areas reuse presented in this paper. However the use of CPN formalism contributes to develop structured models much more easy to maintain and adapt to particular operational conditions in which different heuristics can be designed and tested. As problem definition can vary based on the type of box (homogeneous versus heterogeneous) and input requirement (deterministic versus stochastic) this work is based on the "three-dimensional Bin Packing Problem (BPP)" concept which is characterized by a packing set of nonidentical rectangular cargo-boxes into a minimum number of three-dimensional identical bins or containers, Dowsland (1991). Other scenarios have recently emerged, some of them related to intermodal transport systems, as it is the case of air-cargo, which requires a highly flexible palletizing system.

This paper presents a challenging modelling approach in which the Coloured Petri Net formalism has been used to specify the PLP in such a way that upstream and downstream logistic information flow can be easily formalized to improve the search of feasible solutions for a certain particular industrial context. The most important advance lies in the fact that the model is flexible enough to accept different information flows to tackle the PLP according to the operational context to be optimized, Piera, Zuniga and Mujica, (2009). Thus, different availability aspects can be easily modelled by formalizing the events in CPN that specify the availability of boxes in a local stock, the arrival of boxes from the production system through a conveyor or from a warehouse. In a similar way, the model scope can be extended with downstream transportation aspects such as capacity and weight truck constrains. Coloured Petri Net models supports the specification of time delays associated to events Narciso, Piera and Guasch, (2009), thus the proposed PLP model could also consider time restrictions not only on the delivery of the pallets to support an efficient supply chain management but also on the palletizing operations.

Furthermore, different colours (i.e. attributes) can be added to the PLP model to consider other aspects such as degrees of sturdiness/fragility, weigh category, size ordering, or a stability priority, among others, which can be used as constraints to guide the search through the state space for a feasible or optimal PLP solution, Piera et al. (2004).

The organization of this paper is the following: Section II presents a general description of the palletizing model developed at a Discrete Event System (DES) abstraction level. Section III presents a brief introduction to the CPNs. In Section IV the model is described in detail and in Section V different computational experiments with homogeneous and heterogeneous systems are reported. In Section VI some heuristics are added to the model based on different type of approach and different computational experiments for this model are reported. Finally conclusions are presented in Section VII.

4.2 Discrete event approach to the PLP

Given a set of *n* different types of rectangular-shaped boxes (or arrangement of several such boxes) with known dimensions *lxi*, *lyi*, *lzi* (with $i = 1 \ldots n$) the model solves the orthogonal packing onto a rectangular pallet of fixed dimensions, *slx* * *sly*.

Without a loss of generality, the model considers that the product must be packed orthogonally (i.e. with the edges of the boxes parallel to the edges of the pallet) and can be placed in different layers. Furthermore, boxes to be placed can have a time stamp attached that can be used to specify when the box will be available for packing (i.e. a rough constraint of the production system).

When a box is positioned inside the pallet the space is partitioned or fragmented into several rectangular shaped spaces called *free surfaces*. Figure 4-1 illustrates two free surfaces that are generated after placing a box. The *Total free surface* concept refers to the total available space inside the pallet i.e. the sum of the *n* different free surfaces previously generated. Each time a box is positioned inside the pallet, some information is updated to support a proper description of the pallet state: coordinates, dimensions and orientation of each box, coordinates and dimension of each new free surface generated as a consequence of positioned boxes.

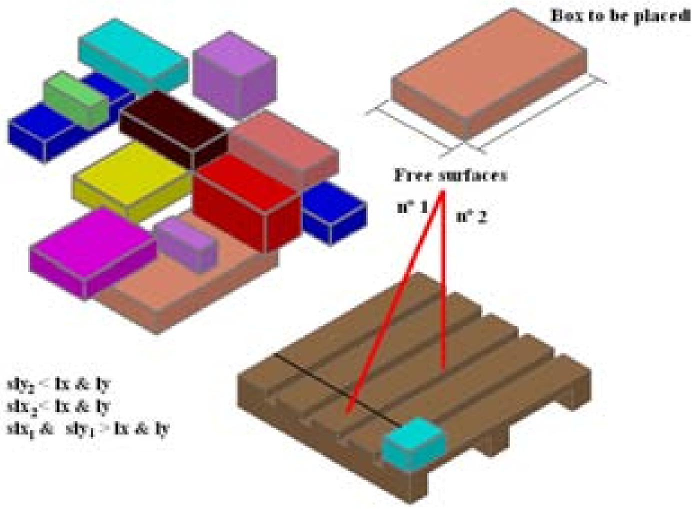


Figure 4-1: Box placement casuistic and free surfaces

To illustrate the importance of a proper state oriented pallet specification of the free surface area, let's consider again Figure 4-1, in which the box placed in the left bottom corner has generated two new free rectangular surface areas. To place another box in the pallet the two free surfaces must be evaluated to determine if the box can be inserted inside one of both areas or it is necessary to compute a new free area as a result of a combination of the two fragmented free areas. Thus, events describing different possibilities for placing a box in a pallet should be computed in an efficient way the different pallet layout configurations.

When a box has to be placed inside the pallet there are two possibilities that can be described as a relationship between boxes dimensions and free surface areas characteristics:

1. the box fits inside a free surface
2. the box does not fit inside a free surface.

By considering again the pallet's configuration described in Figure 4-1, the new box could be placed in the free surface area *nº 1*, but due to dimension constraints the box couldn't be placed in the free surface area *nº 2* (even if the box is rotated). However, there is also a combination of the two contiguous free surface areas that would support the placement of box *nº 2*.

The fragmentation/defragmentation free surface areas has been solved very efficiently, by supporting the CPN specification of virtual boxes, in which a box is fragmented in contiguous virtual boxes that must be placed in contiguous free surface areas. Figure 4-2, illustrates the virtual box concept in which a box to be placed (box *nº 2)* is fragmented in two virtual boxes to be fitted in the free surface areas.

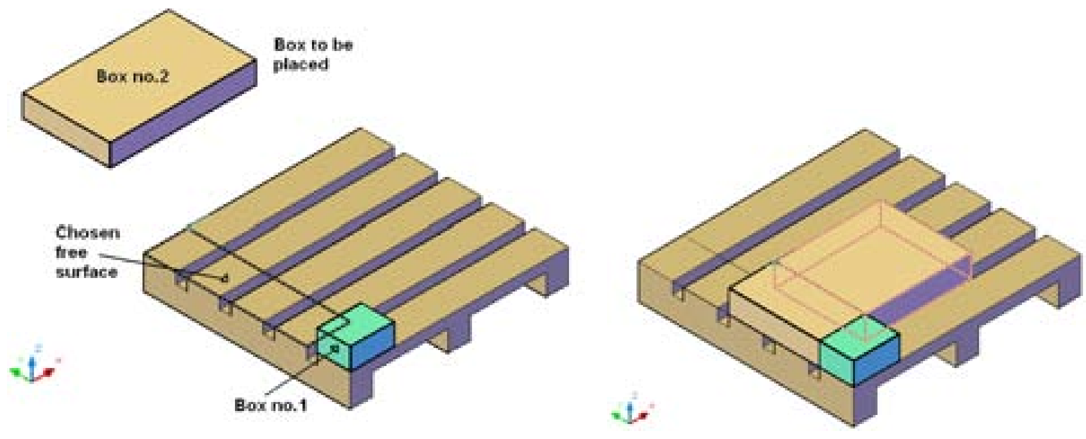


Figure 4-2: Generation of virtual boxes

4.3 Coloured Petri Net optimization approach

Coloured Petri Nets (CPN) according to Jensen, (1997) have proved to be successful tools for modelling complex systems due to several advantages such as the conciseness of embodying both the static structure and the dynamics, the availability of the mathematical analysis techniques, and its graphical nature, Piera et al (2004).

The main CPN components that fulfill the modelling requirements for flexible systems, Piera, Narciso and Buil (2009), are:

- Places: They are very useful to specify both queues and logical conditions. Graphically represented by circles.
- Transitions: They represent the events of the system. Represented graphically by rectangles.
- Input Arc Expressions and Guards: Are used to specify which type of tokens can be used to fire a transition.
- Output Arc Expressions: Are used to specify the system state change that appears as a result of firing a transition.
- Colour Sets: Determines the types, operations and functions that can be used by the elements of the CPN model. Token colours can be seen as entity attributes of commercial simulation software packages
- State Vector: The smallest information needed to predict the events that can appear. The state vector represents the number of tokens in each place, and the colours of each token.

The Colour sets will allow the modeller to specify the entity attributes. The output arc expressions allow to specify which actions should be coded in the event routines associated with each event (transition). The input arc expressions allow to specify the event pre-conditions. The state vector will allow the modeller to understand why an event appears, and consequently to introduce new pre-conditions (or remove them) in the model, or change some variable or attribute values in the event routines to lock enabled events.

From the Operational Research (OR) point of view, a CPN model can provide the following mathematical structures:

- Variables: A variable can be identified for each colour specified in every place node.
- Domains: The domains of the variables can be easily determined by enumerating all the tokens colours specified in the initial state.

- Constraints: Can be obtained straightforward from the arc and guard expressions. Arc expressions can contain constant values, colour variables or mathematical expressions.

From the Artificial Intelligence (AI) point of view, the reachability tree of a CPN model allows to determine:

- All the events that could appear according to a particular system state (Figure 4-3).
- All the events that can set off the firing of a particular event.
- All the system states (markings) that can be reached starting from a certain initial system operating conditions known as initial marking and represented by M0.
- The firing sequence to drive the system from a certain initial state to a desired end-state.

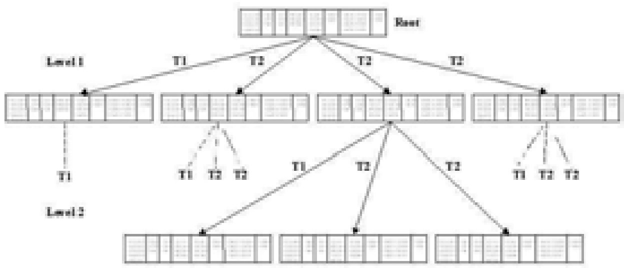


Figure 4-3: First 2 levels of a reachability tree

4.4 PLP CPN specification

The PLP model has been specified in the CPN formalism. The box placement casuistic is decomposed into four set of transitions. The first two set of transitions are casuistic for the box placement (see Figure 4-4) while the other two casuistic are for the virtual box placement.

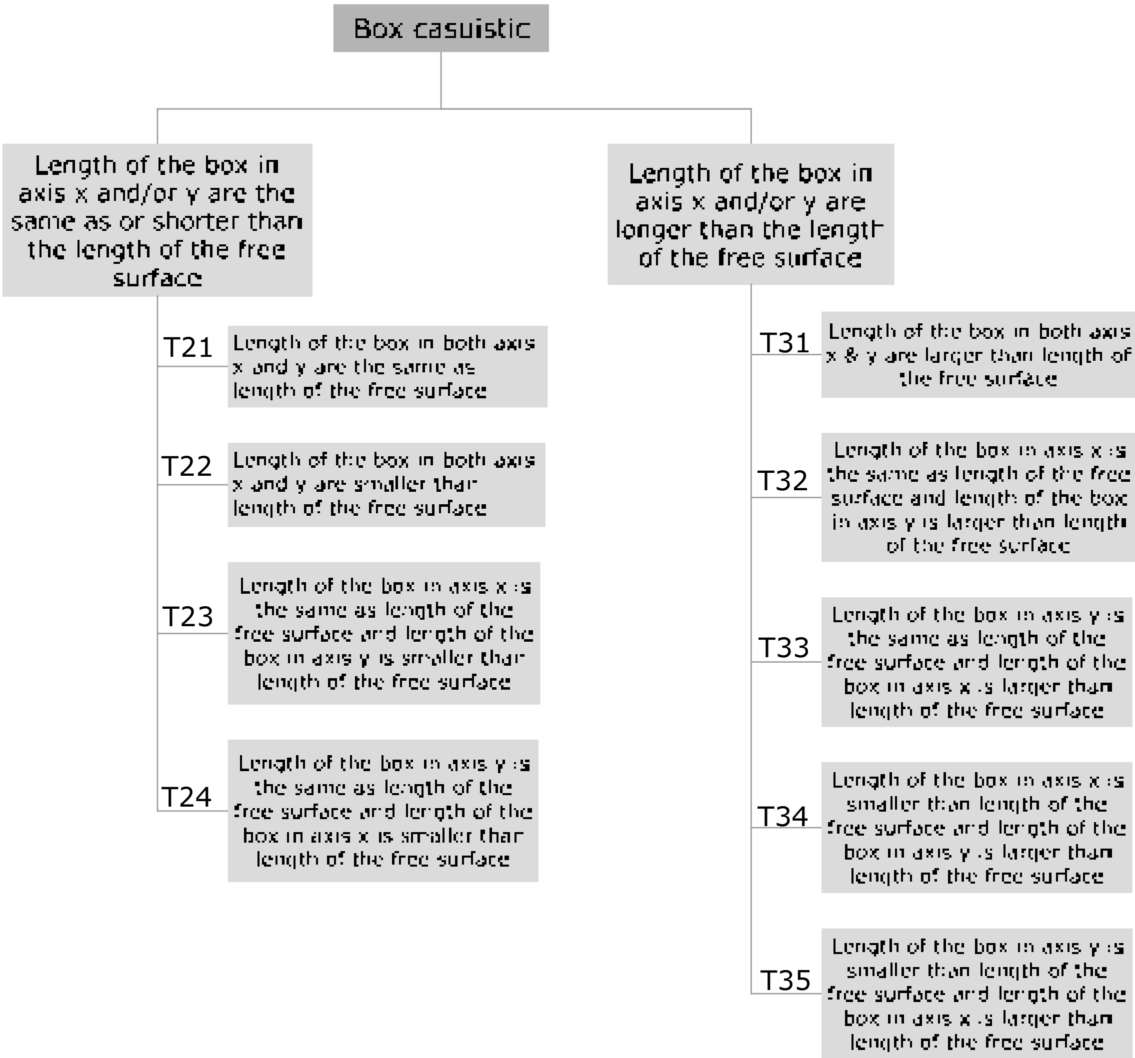


Figure 4-4: Box placement casuistic

As shown in Figure 4-4, when a box does not fit into a free surface, one or more virtual boxes emerge as a consequence of the dimensions and position of the free surface. The placement of these virtual boxes is outlined in Figure 4-5.

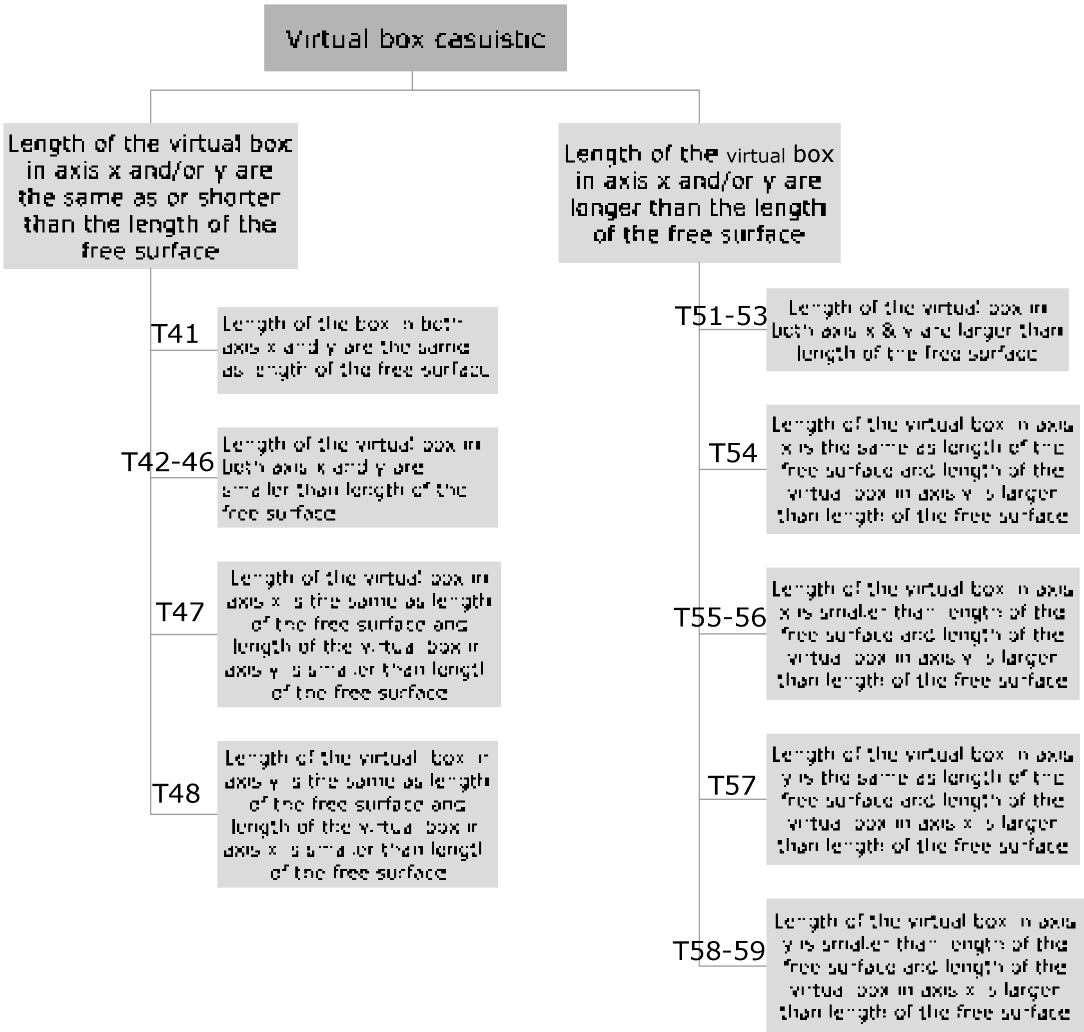


Figure 4-5: Virtual box placement casuistic

Figure 4-6 illustrate the main differences between a subset of transitions (i.e. T42 to T46) that have been generated by another transition (Figure 4-5). It is not hard to see that even if dimensions of the virtual box are the same in each transition, coordinates where placement will be done are not necessary the same. Therefore some restrictions are added to each transition to define each situation shown.

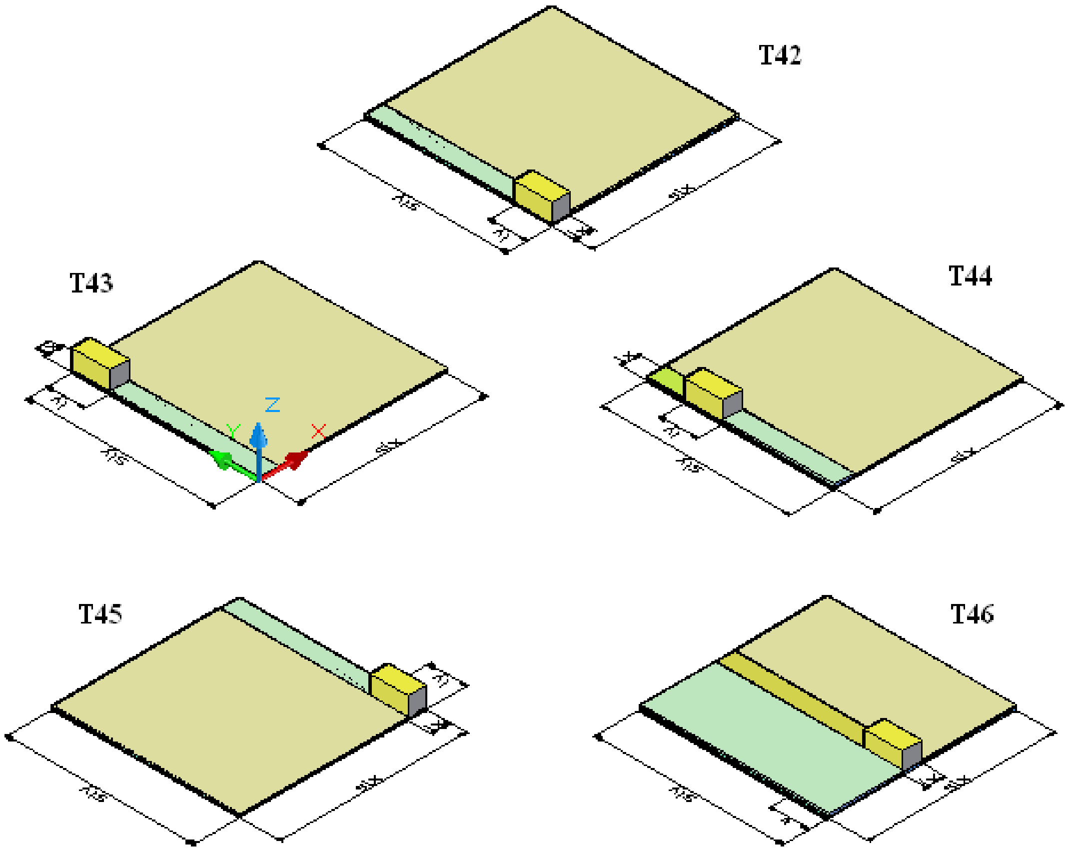


Figure 4-6: Examples of virtual box placement casuistic

Finally, a transition (*T1*) allows *90 º* box rotations as long as they are placed with edges parallel to the pallet's edges, i.e., the placement must be orthogonal, and each box can be rotated only once.

4.4.1 TERMINOLOGY

Table 1and 2 summarize the colours and places used to describe all the information required to fit boxes in a pallet using the abstraction level of the pallet maker process introduced in this section.

Table 4-1: Place specification

Place	Colour	Meaning
P1	$1'(idc, cx, cy, cz, lx, ly, lz, cr, ce)$	Boxes
P2	$1'(scx, scy, slx, sly)$	Free surfaces
P3	$1'(idc, cx, cy, cz, lx, ly, lz, ce)$	Virtual boxes
P4	$1'(ge, gz, gsf, gncv, gnc)$	Global variables

Table 4-2: Colour specification

Colour	Definition	Meaning
idc	Integer	Box identifier
cr	Integer	0: original orientation 1: rotated 90° wrt *z*
ce	Integer	0: not assigned 1: working 2: placed in the pallet
cx	Real	Coordinate *x* where the box is located
cy	Real	Coordinate *y* where the box is located
cz	Real	Coordinate *z* where the box is located
lx	Real	Box length in coordinate *x*
ly	Real	Box length in coordinate *y*
lz	Real	Box length in coordinate *z*
scx	Real	Coordinate *x* where the surface is located
scy	Real	Coordinate *y* here the surface is located
slx	Real	Surface length in coordinate *x*
sly	Real	Surface length in coordinate *y*
ge	Integer	0: A box can be placed in the pallet 1: Box to be assigned 2: Looking for a surface 3: Evaluating the new fractioned surfaces
gz	Integer	Indicates the pallet floor
gsf	Real	Total free surface in the pallet
gncv	Integer	Number of virtual boxes
gnc	Integer	Total number of boxes

4.4.2 EVENT SPECIFICATION EXAMPLES

An example of an event that fits a box in a free surface area when the length *x* and *y* of the box are shorter than the length *x* and *y* of a free surface (see the guard expression). It should be noted that under these state conditions, the free surface used to place the box is fragmented in two new free surfaces that can be used to place future boxes.

Figure 4-7 illustrates the event that formalizes fitting a box into a free surface when the length *x* and/or *y* of the box are longer than the length *x* and *y* of a free surface, respectively. Node *P1* holds tokens describing the boxes to be placed while *P2* holds tokens which contain information that represents the free surfaces. Therefore, two virtual boxes are computed and added in place *P3* in which coordinates and dimensions are hold. *P4* is used to control and coordinate the sequence of events to solve a virtual box placement before any other box could be chosen to be placed in the pallet. Colour *ge* changes from *0* to *1* in the output arc (*T31 -> P4*) to mark that the original box has been divided into one or more virtual boxes; the total free surface is also decremented in according to the portion used by the virtual box (i.e. *sly*slx*) which are the dimensions of the free surface used. The number of virtual boxes *gncv* is incremented in two units, which are the two virtual boxes generated due to the firing of this transition.

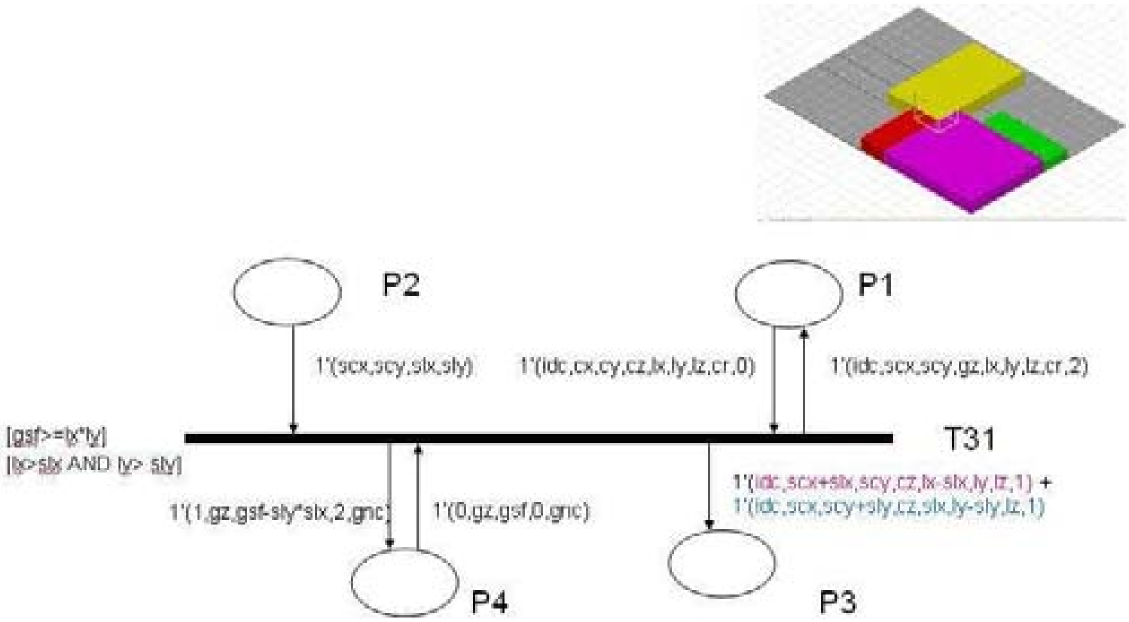


Figure 4-7: T31. Fitting a box with lx>slx and ly>sly

To place a virtual box, two different set of events have been considered; the first set (*T41* to *T48)* represents the placement of a virtual box that do not overcome a free surface, while the second set (*T51* to *T58*) of events support the fitting of a virtual box which does overcome the surface and generates more virtual boxes.

Figure 4-8 illustrates the idea of placing virtual boxes. It is assumed that part of the original box has been placed and it remains only one virtual box to be placed. In this situation, transition called *T58* would be fired (see Figure 4-9), in which a virtual box is placed generating one virtual box, which is indicated by the output arc of place *P3*. Also another free surface is generated, output arc of place *P2*. Finally as explained in the transition called *T31*, total free surface is decremented and the number of virtual boxes keeps steady because one virtual box is placed but another is generated.

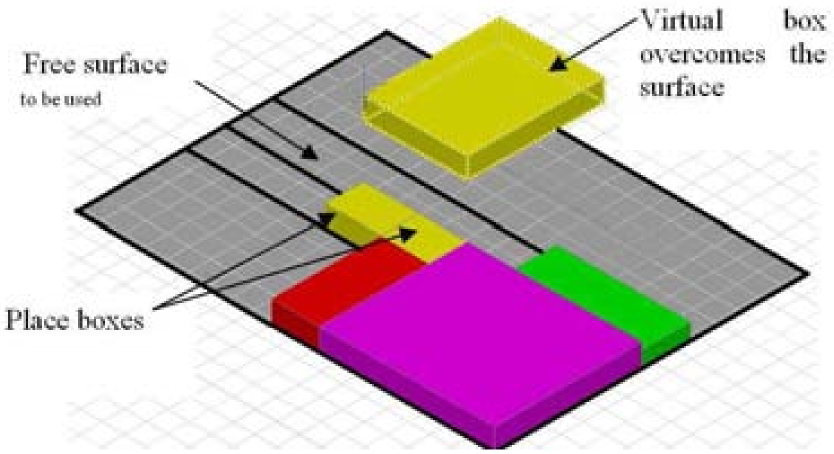


Figure 4-8: Fitting a box with lx>slx, ly<sly, scx=cx & scy=cy.

Additionally to all these events that specify how to place a box into a free surface, there is a particular event that allows changing the orientation of the box in order to fit better in a free surface. This event could happen at any time but can only be fired only once per each box.

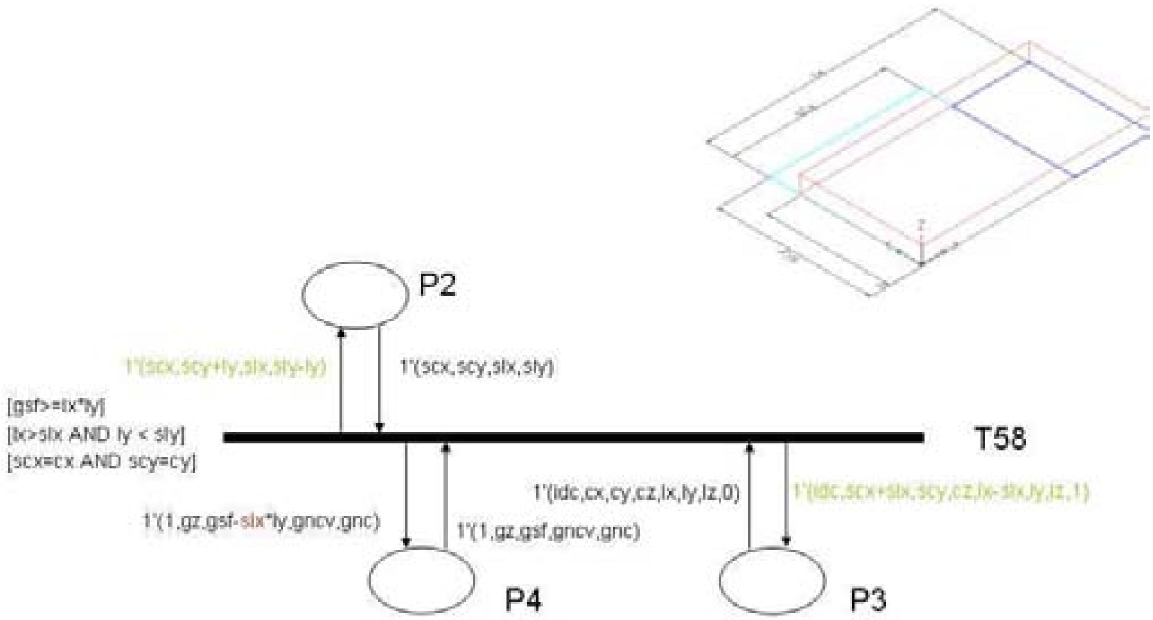


Figure 4-9: CPN for fitting a box with lx>slx, ly<sly, scx=cx & scy=cy.

4.5 Experiments and results

The reachability tree relies on the computation of all reachable states and state changes of the system, and it is based on an explicit state enumeration. Thus, by means of the state space exploration of the CPN model developed, it is possible to check the different combinations in which boxes can be fitted in the pallet, and choose the one that minimizes a certain cost function: free surface area not properly used due to space fragmentation, delays due to boxes time stamps, etc.

A packing pattern of a pallet is said to be *feasible* if the boxes fit completely within a pallet and the specification of this final state consists to force all the tokens in node *P1* to set the colour *ce* with value 2, mathematically represented by the vector:

$$Mf=[*'(*,*,*,*,*,*,*,2),*,*,*] \quad (1)$$

Thus, any state with all the tokens in place *P1* with colour *ce=2* can be considered a feasible solution since all the boxes has been fitted inside the surface.

Several experiments exploring the reachability tree have been performed in two different simulation tools (CPNTools and Piera et all (2004)) to illustrate the benefits of the CPN model. Experiments have been divided based on the box's typology:

- *Case I*: Test data are shown in Table 3. All box types are identical in this case. Homogeneous systems.
- *Case II*: Test data are shown in Table 4. Box types are different in this case. Heterogeneous systems.

Table 4-3: Test data for case I

Test no.	No. of boxes	No. of boxes' type	Dimensions (x, y, z)
1	2	1	100, 50, 10
2	5	1	100, 20, 10
3	10	1	50, 20, 10
4	9	1	30, 30, 10
5	6	1	30, 40, 10

Table 4-4: Test data for case II

Test no.	No. of boxes	Boxes' types	No. of boxes' type	Dimensions (x, y, z)
6	2	2	1	100, 20, 10
			1	100, 80, 10
7	4	4	1	40, 30, 10
			1	40, 70, 10
			1	60, 20, 10
			1	60, 80, 10
8	7	2	3	40, 50, 10
			4	20, 50, 10

Boxes must be accommodated in a surface of *100x100* units Results for a feasible solution of Tests 1 to 5 of *case I* and Test 2 to 8 of *case II* are shown in Table 5 and 6, respectively. In these Tables final marking of all places as well as the graphical representation are shown. Using information on place *P4*, it can be noticed that all boxes have been placed successfully inside the pallet and the free space unused is the minimal. This means that *100*% pallet utilisation can be obtained with all boxes properly placed.

Even feasible solutions are found with both tools, computational time is considerably too large, and therefore two different heuristics have been developed to decrement computational time without losing feasible solutions.

4.6 Specification of heuristic rules in CPN to improve the PLP search

Since the exploration of the whole reachability tree is quite expensive in terms of computer memory requirements and computational time, some heuristics have been designed to avoid the evaluation of certain sequence of events that will not lead a good solution. In Piera et all (2004) and Piera, Mujica and Guasch, (2007), the main aspects of a reachability tree analysis tool implemented to support heuristics and knowledge representation is outlined. This tool has been used to get feasible results solving the PLP using a reduced number of different boxes types by means of formalizing specific knowledge in terms of heuristics

Table 4-5: Feasible solutions for case I

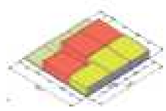
Place	Colour	Graphical representation
	Test 1	
P1	1′(1,0,0,0,100,50,10,0,2)+ +1′(1,50,0,0,100,50,10,0,2)	
P2	empty	
P3	empty	
P4	empty	
	Test 2	
P1	1′(1,0,0,0,20,100,10,1,2)+ 1′(1,20,0,0,20,100,10,1,2) +1′(1,40,0,0,20,100,10,1,2)+1′(1,60,0,0,20,100,10,1,2) +1′(1,80,0,0,20,100,10,1,2)	
P2	empty	
P3	empty	
P4	empty	
	Test 3	
P1	1′(1,0,0,0,50,20,10,0,2)++ 1′(1,0,20,0,50,20,10,0,2) + 1′(1,0,40,0,50,20,10,0,2)+ 1′(1,0,60,0,50,20,10,0,2)+ 1′(1,0,80,0,50,20,10,0,2)+ 1′(1,50,0,0,50,20,10,0,2)+ 1′(1,50,20,0,50,20,10,0,2)+1′(1,50,40,0,50,20,10,0,2)+ 1′(1,50,60,0,50,20,10,0,2)+1′(1,50,80,0,50,20,10,0,2)	
P2	empty	
P3	empty	
P4	empty	
	Test 4	
P1	1′(1,0,0,0,30,30,10,0,2)+ 1′(1,0,30,0,30,30,10,0,2)+ 1′(1,0,60,0,30,30,10,0,2)+ 1′(1,30,0,0,30,30,10,0,2)+ 1′(1,30,30,0,30,30,10,0,2)+1′(1,30,60,0,30,30,10,0,2) + 1′(1,60,0,0,30,30,10,0,2)+ 1′(1,60,30,0,30,30,10,0,2)+ 1′(1,60,60,0,30,30,10,0,2)	
P2	1′(0,90,30,10)+1′(0,30,90, 30,10)+1′(60,90,30,10)+ 1′(90,0,10,100)	
P3	empty	
P4	1′(0,0,1900,0)	
	Test 5	
P1	1′(1,0,0,0,40,30,10,1,2)++ 1′(1,0,30,0,30,40,10,0,2)++ 1′(1,40,0,0,30,40,10,0,2)++1′(1,40,40,0,30,40,10,0,2)+ 1′(1,70,0,0,30,40,10,0,2)++1′(1,70,40,0,30,40,10,0,2)	
P2	1′(0,70,30,30)+1′(30,30,10,70)+1′(40,80,30,20)+ 1′(70,80,30,20)	
P3	empty	
P4	1′(0,0,2800,0)	

Table 4-6: Feasible solutions for case II

Place	Colour	Graphical representation
	Test 6	
P1	1′(1,0,0,0,100,80,10,0,2)++1′(1,0,80,0,100,20,10,0,2)	
P2	empty	
P3	empty	
P4	empty	
	Test 7	
P1	1′(1,0,0,0,60,80,10,0,2)++ 1′(1,0,80,0,60,20,10,0,2)++ 1′(1,60,0,0,40,70,10,0,2)++1′(1,60,70,0,40,30,10,0,2)	
P2	empty	
P3	empty	
P4	empty	
	Test 8	
P1	1′(1,0,0,0,40,50,10,0,2)++ 1′(1,0,50,0,40,50,10,0,2)++1′(1,40,0,0,20,50,10,0,2)++ 1′(1,40,50,0,20,50,10,0,2)+1′(1,60,0,0,40,50,10,0,2)++ 1′(1,60,50,0,20,50,10,0,2) 1′(1,80,50,0,20,50,10,0,2)	
P2	empty	
P3	empty	
P4	empty	

.

4.6.1 HEURISTIC BASED ON TYPOLOGY BOXES

A heuristic has been developed and implemented in the model so boxes are placed by groups of the same type (i.e. boxes of the same dimensions). Thus, if a box of certain type is chosen, the model is forced to place all boxes of this type before any other box type could be chosen.

This heuristic is specified by the introduction of two more transitions to the model, two places (see Table 7) and two colours. These new colours are *nc* and *tp*; colour *tp* is a control variable which can take a *0* value if the box type has never been picked and *tp=1* if it has been picked; the other colour added to the model is *nc*, representing the number of boxes of the same type.

Table 4-7: Changes in place specification

Place	Colour	Meaning
P1	1'(*idc*, *cx*, *cy*, *cz*, *lx*, *ly*, *lz*, *cr*, *tp*, *nc*)	Boxes
P	1'(*tp*)	Type box
CO	1'(*idc*, *cx*, *cy*, *cz*, *lx*, *ly*, *lz*, *cr*)	Placed boxes

Place *P1* has been modified by removing the colour *ce* and adding the two new colours *tp* and *nc* to determine if a certain box type has been already placed in the pallet.

To allow a change on the type of boxes to be fitted in the pallet, a second transition *TC* has been implemented that is activated when all the boxes of the same type have been placed (colour $nc = 0$). Once *TC* has been fired, colour *tp* is updated from *0* to *1* to activate the selection of a new type of box (place *CO* is used to trace information changes). Several experiments exploring the reachability tree have been performed and results are presented in case III.

- Case III: Test data are shown in Table 8. Heterogeneous systems using heuristic based on typology boxes.

Table 4-8: Test data for case III

	No. of boxes	Boxes' types	No. of boxes per type	Dimensions (*x*, *y*, *z*)
Test 9	8	3	2	60, 40, 10
			2	40, 35, 10
			4	30, 20, 10
Test 10	9	3	2	30, 40, 10
			5	40, 15, 10
			2	30, 60, 10
Test 11	15	4	4	10, 25, 10
			4	20, 40, 10
			3	20, 15, 10
			4	40, 30, 10
Test 12	16	5	6	10, 35, 10
			2	30, 15, 10
			2	40, 40, 10
			1	20, 20, 10
			5	20, 30, 10

Boxes must be accommodated in a pallet surface of *100x100* units.

Results for a feasible solution of tests 9 to 12 of *case III* are shown in Table 9. In this Table the final marking of all places as well as the graphical representation is shown. Using information on place *P4*, it can be noticed that all boxes are placed successfully inside the pallet and the free space unused is minimal. This means that *100%* pallet utilisation can be obtained with all boxes properly placed therefore this heuristic reaches a feasible solution.

Table 4-9: Feasible solutions for case III

Place	Colour	Graphical representation
	Test 9	
P1	1′(1,40,0,0,60,40,10,0)++ 1′(1,40,40,0,60,40,10,0)++1′(2,0,0,0,40,35,10,0)++ 1′(2,0,35,0,40,35,10,0)++ 1′(3,0,70,0,20,30,10,1)++ 1′(3,20,70,0,20,30,10,1)++ 1′(3,40,80,0,30,20,10,0)++1′(3,70,80,0,30,20,10,0)	
P2	empty	
P3	empty	
P4	empty	
	Test 10	
P1	1′(2,40,0,0,40,15,10,1)++ 1′(2,55,0,0,40,15,10,1)++ 1′(1,0,0,0,30,40,10,1)++ 1′(1,0,30,0,30,40,10,1)++ 1′(2,70,0,0,40,15,10,1)++ 1′(2,0,60,0,40,15,10,1)++ 1′(2,15,60,0,40,15,10,1)++1′(3,40,40,0,30,60,10,1)+ 1′(2,40,70,0,30,60,10,1)	
P2	1′(85,0,15,40)+ 1′(30,60,10,40)	
P3	empty	
P4	empty	
	Test 11	
P1	1′(1,0,0,0,10,25,10,0)++ 1′(1,10,0,0,10,25,10,0)++ 1′(1,25,0,0,10,250,10,0)++ 1′(1,10,25,0,10,25,10,0)++1′(2,20,0,0,20,40,10,0)++ 1′(2,40,0,0,20,40,10,0)++ 1′(2,60,0,0,20,40,10,0)++ 1′(2,80,0,0,20,40,10,0)+ 1′(3,0,65,0,20,15,10,0)++ 1′(3,0,70,0,20,15,10,0)++ 1′(3,0,85,0,20,15,10,0)++ 1′(4,20,40,0,20,15,10,0)++ 1′(4,60,40,0,20,15,10,0)++1′(4,20,70,0,20,15,10,0)++ 1′(4,60,70,0,20,15,10,0)	
P2	1′(0,95,5,20)	
P3	empty	
P4	1′(0,0,100,0,0)	
	Test 12	
P1	1′(2,0,0,0,40,40,10,0)++ 1′(2,0,40,0,40,40,10,0)++ 1′(5,0,80,0,20,30,10,1)++ 1′(5,40,0,0,20,30,10,1)++ 1′(5,40,20,0,20,30,10,1)++1′(5,40,40,0,20,30,10,1)++ 1′(5,40,60,0,20,30,10,1)++1′(4,30,80,0,20,20,10,0)++ 1′(2,70,0,0,30,15,10,1)++ 1′(2,85,0,0,30,15,10,1)++ 1′(1,70,30,0,10,35,10,0)++1′(1,70,65,0,10,35,10,0)++ 1′(1,80,30,0,10,35,10,0)++1′(1,80,65,0,10,35,10,0)++ 1′(1,90,30,0,10,35,10,0)++ 1′(1,90,65,0,10,35,10,0)	
P2	1′(50,80,20,20)	
P3	empty	
P4	1′(0,0,400,0,0)	

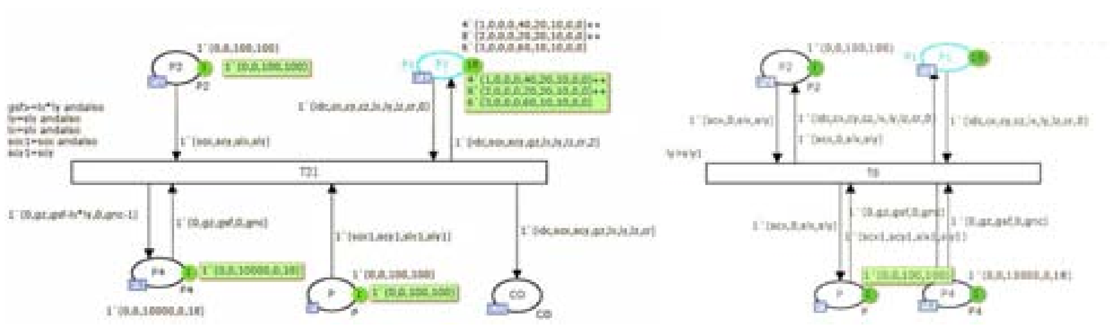
4.6.2 BASED ROW PLACEMENT HEURISTIC

A second heuristic has been designed and integrated in the CPN model so boxes are placed by rows independent of the box's type. Thus, a box is placed following the same coordinates in the axis *y* of the previous box. A new row is initialized by fitting a new box, when no more boxes can be fitted in the previous row.

This heuristic is specified by means of a new transition (*T8*) (see Figure 4-10a), and the rest of transitions have been modified by two places, *P* and *CO* (see Table 10 and Figure 4-10b) and four colours (*scx1, scy1,slx1,sly1*) to represent the coordinates and dimensions of the new row in axis *x* and *y*. When a row is full of boxes or there is not a box that fits in the row, a change of row is allowed.

Table 4-10: Changes in place specification

Place	Colour	Meaning
P	1'(*scx*1, *scy*1, *slx*1, *sly*1)	Free surface of new row
CO	1'(*idc*, *cx*, *cy*, *cz*, *lx*, *ly*, *lz*, *cr*)	Placed Boxes



a) b)

Figure 4-10: Heuristic based on typology boxes. a)New transition. b) Modified places and colours

A place called *P* is added to the model and it is used to store coordinates and dimensions of free surfaces that might be used in the next row. A new place *CO* was introduced to store placed box information.

Several experiments exploring the reacheability tree have been performed in CPN Tools.

- Case IV: Test data are shown in Table 11. Heterogeneous systems using heuristic based on row placement.

Table 4-11: Test data for case IV

	No. of boxes	Boxes' types	No. of boxes per type	Dimensions (x, y, z)
Test 13	8	3	3	50, 30, 10
			2	20, 40, 10
			3	30, 30, 10
Test 14	11	3	5	40, 20, 10
			3	40, 30, 10
			3	20, 30, 10
Test 15	13	3	3	30, 30, 10
			8	10, 30, 10
			2	40, 30, 10
Test 16	16	3	5	30, 20, 10
			5	70, 10, 10
			6	20, 20, 10

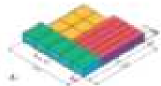
Boxes must be accommodated in a pallet surface of *100x100* units.

Results for a feasible solution of tests 13 to 16 of *Case IV* are shown in Table 12. In this Table the final marking of all places as well as the graphical representation is shown. Using information on place *P4*, it can be noticed that the all boxes are placed successfully inside the pallet and the free space unused is the minimal. This means that *100 %* pallet utilisation can be obtained with all boxes properly placed; therefore this heuristic reaches a feasible solution.

Both heuristics has been implemented mainly by specifying new guard expressions in the box placement transition. In a similar way to priorize the use of small/large fragmented free spaces areas new guard expressions could be designed to choose the most promising tokens from place node *P2* according to the token (box) chosen from place node *P1*.

Table 4-12: Feasible solutions for case IV

Table 12. Feasible solutions for case IV.

Place	Colour	Graphical representation
	Test 13	
P1	1′(1,20,0,0,50,30,10,0)++ 1′(1,20,30,0,50,30,10,0)++1′(1,20,60,0,50,30,10,0)++ 1′(1,0,0,0,20,40,10,0)++ 1′(1,0,40,0,20,40,10,0)++ 1′(1,70,0,0,30,30,10,0)++ 1′(1,70,30,0,30,30,10,0)++1′(1,70,60,0,30,30,10,0)	
P2	1′(0,90,50,10)+1′(50,80,20,20)++ 1′(70,90,30,10)	
P3	empty	
P4	1′(0,0,1200,0,0)	
	Test 14	
P1	1′(1,40,0,0,40,20,10,0,2)++1′(1,40,20,0,40,20,10,0,2)+ 1′(1,40,40,0,40,20,10,0,2) 1′(1,40,60,0,40,20,10,0,2)+1′(1,40,80,0,40,20,10,0,2)+ 1′(1,80,0,0,20,30,10,0,2) 1′(1,80,30,0,20,30,10,0,2)+1′(1,80,60,0,20,30,10,0,2)+ 1′(1,0,0,0,40,30,10,0,2) 1′(1,30,0,0,40,30,10,0,2)++1′(1,60,0,0,40,30,10,0,2)	
P2	1′(40,90,20,10)++ 1′(60,90,40,10)	
P3	empty	
P4	1′(0,0,60,0,0)	
	Test 15	
P1	1′(1,0,0,0,30,30,10,0)++ 1′(1,30,0,0,30,30,10,0)++ 1′(1,60,0,0,30,30,10,0)++ 1′(1,0,30,0,30,10,10,0)++ 1′(1,10,30,0,30,10,10,0)++1′(1,20,30,0,30,10,10,0)++ 1′(1,30,30,0,30,10,10,0)++1′(1,40,30,0,30,10,10,0)+ 1′(1,50,30,0,30,10,10,0)1′(1,60,30,0,30,10,10,0)++ 1′(1,90,0,0,30,10,10,0)++ 1′(1,0,60,0,40,30,10,0)1′(1,70,60,0,40,30,10,0)	
P2	1′(30,70,30,30)++ 1′(60,60,40,40)	
P3	empty	
P4	1′(0,0,2500,0,0)	
	Test 16	
P1	1′(1,0,0,0,30,20,10,0,2)++ 1′(1,0,20,0,30,20,10,0,2)++1′(1,0,40,0,30,20,10,0,2)++ 1′(1,0,60,0,30,20,10,0,2)++1′(1,0,80,0,30,20,10,0,2)++ 1′(1,30,0,0,70,10,10,0,2)++ 1′(1,30,10,0,70,10,10,0,2)+1′(1,30,20,0,70,10,10,0,2)+ 1′(1,30,30,0,70,10,10,0,2)+ 1′(1,30,40,0,70,10,10,0,2)+1′(1,30,50,0,20,20,10,0,2)+ 1′(1,30,70,0,20,20,10,0,2) 1(1,50,50,0,20,20,10,0,2)+ 1′(1,50,70,0,20,20,10,0,2)+ 1′(1,70,50,0,20,20,10,0,2)+ 1′(1,70,70,0,20,20,10,0,2)	
P2	1′(30,90,20,10)++1′(50,90,20,10)++ 1′(70,90,20,10)++1′(90,50,10,50)	
P3	empty	
P4	1′(0,0,1100,0,0)	

4.7 Conclusions and further work

A discrete event approach to optimize the PLP has been specified in CPN formalism. One of the most important features of the developed model is the flexibility to support production and distribution constraints. The definition of new colours attached to box tokens, could be used as new prerequisites in the PLP solution by considering aspects such as: weight, size and stability constraints.

Despite the examples presented in this paper focus on the which illustrate the static pallet packing problems; the CPN model can be extended to a Timed Coloured Petri Net model in which time components (i.e. simulation clock and time stamps) can used to tackle the PLP as part of a supply chain system. Thus, the specification of a new transition to feed boxes in place node P1 could be used to represent box availability.

The PLP packing strategy has been developed without considering extra constraints that would not affect operational benefits; otherwise the space solution would be too rigid and therefore incapable of managing the inherent diversity of heterogeneous pallet problems. The heuristics formalized in CPN illustrate the flexibility of adapting the model to obtain better computer performances when optimizing the PLP without losing feasible solutions.

For practical application, the model will be adapted with weight factors and delays to optimize pallet operations in a real industrial context. As a future work, the model will be adapted to consider the air cargo operations, in which it is well known that bays in most passenger aircrafts, fly empty because the time required to load non used passenger belies overcomes acceptable turnaround times. Available weight and volume is known at the very last moment, once all passenger baggage has been checked, which usually is 30 minutes before flight departure. Thus, time aspects together with volume and weight constraints will be considered in the design of new heuristics to optimize the palletizing operation in air cargo platforms.

4.8 Acknowledgments

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5 INTEGRATING AND SEQUENCING FLOWS IN TERMINAL MANEUVERING AREA BY EVOLUTIONARY ALGORITHMS

Abstract

This paper presents a new approach for merging multiple aircraft flows in a Terminal Maneuvering Area (TMA). This work is motivated by the current overloaded airspace near large airports and the need of more efficient methods to help controllers. Some attempts to alleviate airspace congestion such as the minimum spacing requirements, negotiation of voluntary reductions in scheduled service, and the construction of additional runways at major airports have been done. Even though, more fundamental changes are needed to improve the use of available air capacity. Present research consists of a new approach to optimize a set of aircraft planned to land at a given airport; it is proposed to merge the incoming flows from different routes by mean of speed and path changes. Due to the high combinatoric induced by such a problem, a stochastic optimization algorithm has been developed in order to propose to each aircraft a new route and speed profile. Those changes aim to remove conflicts at merging points and to maintain separation of aircraft following the same route link according to their wake turbulence constraint. The optimization criteria is based on the minimum deviation from the initial path planning. This algorithm has been successfully applied to Gran Canaria airport in Spain with real traffic demand samples for which conflict free flow merging is produced smoothly with optimal runway feeding.

5.1 Introduction

Future demand in Air Traffic Management (ATM) systems is expected to increase at an average yearly rate of 2.2 to 3.5 in the long term period up to 2030 [12]. This future situation will generate airspace sectors that operate at or above its current capacity, hence different ATM modernization projects have been started. The Single European Sky ATM Research (SESAR) launched by the European Community and the Next Generation Air Transportation System (NextGen) which launched by US government are future projects aim to ensure the safety and fluidity of air transport over the next thirty years.

These concepts address all services related to air navigation specially Air Traffic Flow Management (ATFM) which supports the use of available airspace effectively, including airport capacity and therefore, its importance has been increased significantly. Hence, major benefits can be expected if areas with a high traffic density like the Terminal Maneuvering

Area are analysed to assess the performance of new ATM concepts, like 4D-trajectory planning and strategic deconfliction allowing ATC efficient procedures to predict conflicts among trajectories. As one of the bottlenecks impeding ATM performances is the merging arrival operations into the TMA. This work is mainly focused on optimizing the number of conflicts to improve capacity into the TMA sector.

The Terminal Maneuvering Area or Terminal Control Area (TMA) is a block of airspace class around airport; it is a special type of airspace designed to handle aircraft arriving to and departing from airports and perhaps one of the most complex types of airspace. Current TMA are being forced to accept more and more flights each day, and departure pushes to accommodate late arriving flights; as a consequence, delay flight are induced causing further up & downline disruptions. This, plus the inherent random nature of the arrival times are some of the reasons what make TMA as one of the main bottleneck on ATM. These random arrivals, must be converted into an orderly stream while merging aircraft flows coming from different entry points, commonly done in a short time horizon (about 45 minutes) [1].

Therefore, there is a need for tools that allow an efficient TMA which minimize the deviation between desired and conflict free trajectory for each aircraft while merging multiple flows into the TMA and delivering precisely spaced to the runway threshold. Predictable arrival flows where aircraft land at a specified time, enables ground controllers to issue a more efficient TMA flow system. Moreover, it provides shorter and safetier flights using more efficient airspace by increasing airspace capacity [15].

5.2 Overview

The arrival phase of flights typically starts when the aircraft leave their cruise level in En-Route phase and ends when aircraft reach the Final Approach Fix (FAF) as depicted in Figure 5-1. Aircraft arriving to airports in terminal areas are organized in arrival streams. To build such streams, the individual paths of each aircraft have to be gradually merged. An aircraft approaching is still mainly controlled by ATC with means of radar vectoring where ATC sends additional instructions to aircraft, depending on the actual traffic, to avoid dangerous encounters. Finally, a sequence and merge procedure is made to position aircraft into a single stream (or multiple streams if multiple runways are being used). They must recognize and select the proper technique by which they can alter an aircraft's position within a flow or, the spacing between the leading and the following aircraft. Although this method is efficient and flexible, it is highly demanding for air and ground sides under high traffic load conditions, as it imposes rapid decisions for the controller and time-critical execution by the flight crew.

With the introduction of more Area Navigation (RNAV) arrival and departure procedures, there are potential benefits to be achieved such as; reducing the need to vector aircraft; reduced voice communication; improved situational awareness; reduced flying time and distance; and, improved predictability. RNAV procedures refer to the ability to execute point to point navigation. Standard Instrument Departures routes (SIDs) and Standard Terminal Arrival Route (STARs) are both very similar in many aspects e.g. offering the pilot pre-planned Instrumental Flight Rule (IFR) procedures. STARs are designed to expedite ATC arrival procedure and facilitate the transition between en-route and instrument approach segment as well as to streamline approach flows and to give a more regular approach to an airport. Incoming flows are progressively merged into a single flow for each active landing runway. As example of a STAR, Figure 5-2 presents Gran Canaria TMA.

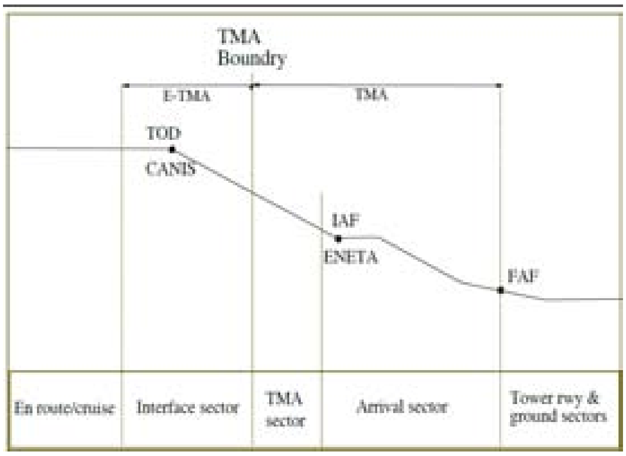

Figure 5-1: Control phases and sectors for the arrival phase of flight

The introduction of RNAV at airports allows operations, based on a common set of design and operational principles, to ensure consistent levels of flight safety. The enhanced predictability and repeatability of RNAV procedures leads to efficiency and environmental benefits being afforded to both airspace users and air navigation service providers.[10]. These procedures should rely on appropriated navigation aids such as instrument assisted landing systems and satellites. The development and application of the Global Positioning System (GPS) and the Automatic Dependant Surveillance Broadcast (ADS-B) allows aircraft to obtain highly accurate positional and directional information about them and other nearby aircraft. [15]

The objective of the algorithm is to effectively merge the arrival flows while keeping aircraft on lateral navigation. This will allow to decrease ATC workload and tactical intervention while keeping a safety separation distance and a efficient landing sequence.

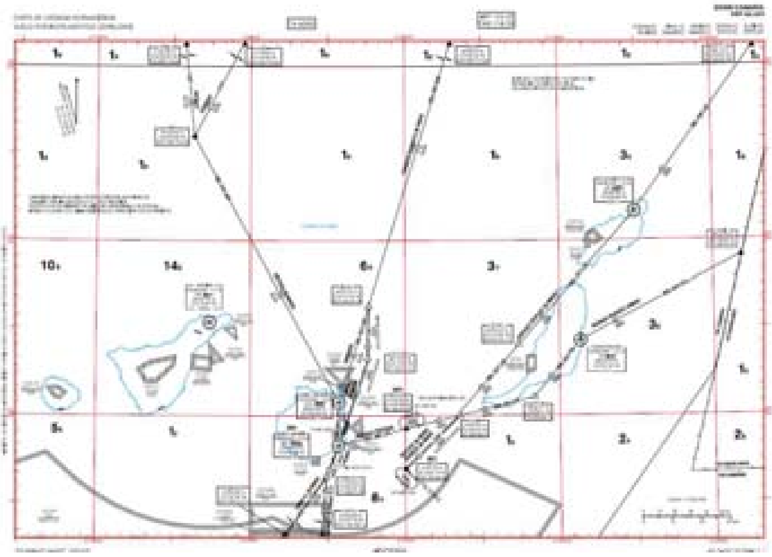

Figure 5-2: Gran Canaria STAR

5.3 *Previous Related Works*

Researchers have been studying the problems related to ATM and diverse traffic control strategies have been proposed. Conflict Detection and Resolution (CD&CR) algorithms have been designed to improve ATM performance. A search of the literature was conducted to identify concepts related to terminal merges and sequence problems as part of these traffic control strategies.

An overview of different CD&CR algorithms is being provided in [17] where over 60 different methods have been analysed and classified. Some of the methods presented are currently in use or under operational evaluation for example [13], the user interface of TCAS.

Some of these methods include tactical approaches focusing on resolving immediate conflicts, with limited consideration of future post-conflict routing and planning. Most of the methods are designed for en-route sectors and based on Optimization approaches to treat the CD&CR problem such as; Genetic Algorithms as in [20] where autonomous aircraft are enable to maneuver freely while maintaining separation assurance from traffic and area hazards; Other CR algorithm, which uses a combination of pattern based maneuvers and Genetic Algorithms to achieve resolution, is presented in [24]; The Ant Colony Optimization (ACO) algorithm has also been applied to solve problems involving autonomous aircraft by applying the path planning problem, [8]; or The developed a mathematical model is formulated as a mixed integer linear program in [23] using concepts based on speed control and flight-level assignments for conflict resolution over predefined routes; other approach applying Linear Programming is [21] where a system of multiple aircraft is de-conflicted by applying the path planning problem among given waypoints. Semi-definite Programming is utilized in [11] where each aircraft proposes its desired heading while a centralized air traffic control authority resolves any conflict arising between aircraft. The approaches mentioned above are some of the most interesting works and concepts to deal with the CD&CR problem.

In [4] a broader suite of concepts have being investigated to address merging and spacing problems arising from structured RNAV and Required Navigation Performance (RNP) routes in the terminal environment referred to as Spacing of Performance-based Arrivals on Converging Routes (SPACR). It addresses the near term merging and spacing problem. A method to merge arrival flows of aircraft without using heading instructions is presented in [5], [18], [14], [10]. The principle is to achieve the aircraft sequence on a point with conventional direct-to instructions, using predefined legs at iso-distance to this point for path shortening or stretching.

Different approaches for the landing sequence problem have been also studied such as [3] based on Linear Programming which solves the static case presenting a mixed-integer zero-one formulation of the problem together with a population heuristic algorithm. A Dynamic-Programming-based approach which used a method called Constrained Position Shifting (CPS) as in [1] and [6] and [2] is another class of algorithms that is able to handle commonly-encountered operational constraints for the sequence problem.

The algorithm developed in this paper will aim to find the optimal trajectory and the optimal distance to be flown for a set of aircraft using Genetic Algorithms. A new combinatorial optimization algorithm to detect and solve conflicts into the TMA is presented. The algorithm is based on the premise of achieving an optimum system-wide improvement in performance instead of accurately and precisely space individual aircraft. It was also based on the idea that a following aircraft, on the same flight path as the lead, would maintain distance-based, rather than a time-based, spacing interval from the preceding aircraft.

The reminder of this works is as follows; the hypotheses needed to formulate the CD&CR optimization problem, the assumptions made, and the Mathematical Modeling is given in the Problem modelling section. Conflict avoidance constraints are formulated as part of the resolution strategy. In the next section, Evolutionary Algorithms are introduced. and the Genetic Algorithm approach is presented in the section called Application to our problems. In the result section, numerical examples are introduced and solved from a sample simulation study of 35 and 50 aircraft. Conclusions are discussed at the end of the paper.

5.4 Problem Modelling

Three cases to avoid possible conflicts are considered in the work of [21]:

1. Aircraft is allow to change speed but trajectory remains fixed. This case is called the velocity change problem (VC problem);

2. Aircraft fly at the same speed profile and it is only allowed to change its trajectory. This case is called the heading angle change problem (HAC problem).

3. the mix of both HAC and VC problem.

The present approach belongs to the third category presented above; conflicts can be avoided by speed regulations or/and path changes. Merging and sequencing arrival flows requires the ability to speed up or delay aircraft, specially in dense traffic areas, speed regulations may not be sufficient and the use of an alternative trajectory may become necessary.

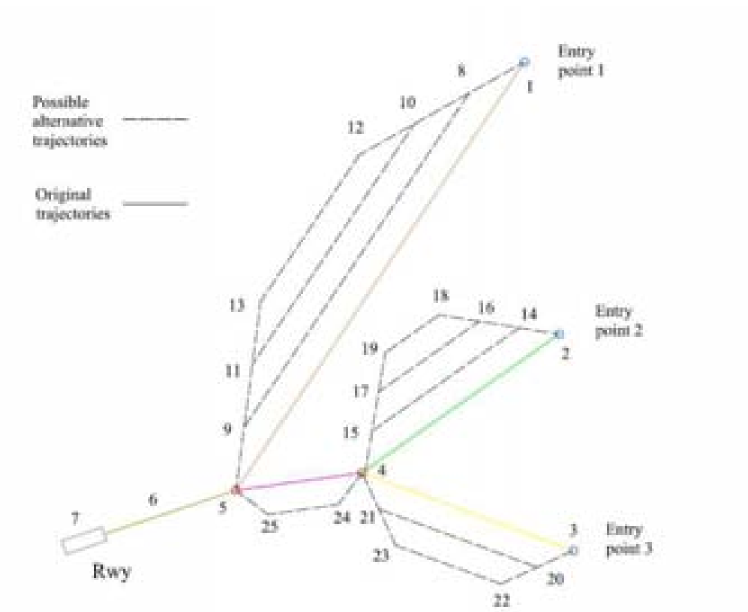

Figure 5-3: TMA configuration example

The system architecture proposed in this work consist of a route network compose by sub-routes in which aircraft are allowed to fly as illustrated in Figure 5-3. Each route has a defined number of sub-routes designed to change path if necessary to solve conflicts. Sub-routes have a predefined length which depend on the length of the original route. Lateral deviation provides the controller and pilot with improved situational awareness. Sub-routes are properly separated laterally, and are composed of links; A link is defined as a portion of a route which connect two waypoints.

To illustrate these concepts, see Figure 5-3; A trajectory is formed from Entry point 3 (or Node No.3) to runway (or Node No.7) passing by Node No.4 and 5. For this original trajectory, 3 sub-routes are defined between Node No.3 and Node No.4, and one sub-route from Node No.4 to Node No.5.

The core problem that is considered on this work is to find conflict free trajectories for a given set of aircraft landing at the same airport by changing their paths and (or) their speeds. Two kind of conflicts will be considered:

- Node Conflict : Minimum space separation has to be manage between successive aircraft flying over the same node.

- Link Conflict : aircraft flying on the same link has to be separated by a minimum separation distance depending on the aircraft's wake turbulence category.

When the separation between two planes is smaller that the minimum separation criteria then a Conflict is Detected (CD). The separation criteria (SC) is due to many factors; first of all, there are aerodynamic considerations; the risk of instability if an aircraft interacts with the wake-vortex turbulence of another aircraft landing or taking off before it; SC also depends on the class of the two aircraft (the leading and the trailing); another one depends on the density of air traffic and the region of the airspace, to mention some factors.

A largely accepted value for horizontal minimum safe separation between two aircraft at the same altitude is 5 nmi in general enroute airspace; this is reduced to 3 nmi in approach sectors for aircraft landing and departing. As different rules exist, separation standards are established by the International Civil Aviation Organization (ICAO). The nominal horizontal minimum spacing interval that will be considered in this work are given in Table I.

Table 5-1: Separation Minima [NM] ICAO DOC-4444

	heavy	medium	light
heavy	4	3	3
medium	5	3	3
light	6	4	3

Some assumptions and simplifications were made in the modeling and execution of the experiment as in [9]. In the model, aircraft trajectories were entirely deterministic. Aircraft executed their planned trajectories and conflict resolution trajectories perfectly, no data-link transmission delays, nor pilot-action delays. Uncertainties in the estimation of aircraft position or unexpected wind fields are not consider. It should be pointed out, that in absence of wind the TAS speed can also be considered as Ground Speed. As such, trajectory conflicts could be predicted with perfect accuracy over any time horizon, and resolution trajectories could be assured to be conflict free. Once a resolution trajectory was determined by the automation, it was executed immediately and precisely. The aircraft are assumed to fly highest/lowest permissible speeds over each flight segment (20% of its average GS) and they are assumed to fly within a fixed altitude layer.

The routes from different directions towards final approach are adequately separated to avoid merging of traffic; and lastly, arrival traffic management initiatives such as miles in trail restrictions, time-based metering, or ground-delay programs were not modelled.

5.4.1 MATHEMATICAL MODELING

The TMA has been modeled by a graph *G ={N,A}* as shown on Figure 5-3 for which *N* is the set of nodes and *A* is the set of links. This graph gathers together the original links (links *{(1;5); (2;4); (4;5); (3;4); (5;7)}* on Figure 5-3) and the sub-routes links for alternative options (for instance link *(4;5)* on Figure 5-3 may be substituted by the sub-route *{(4;24); (24;25); (25;5)}*). For each link *li* the set of alternatives is noted as *alt(li)*.

Let *F* be the set of flights planned to land in a given time horizon *[0;Tmax]*. For each flight *fi* in *F* we know the following:

- *ei* : entry point of flight *fi* in the TMA. Such entry points are nodes in the graph (*{1;2;3}* in our case) ;
- *ti* : time of flight *fi* at entry point.
- *vi* : speed of aircraft (*fi*)
- *wti* : wake turbulence category (heavy, medium, light)

For a given route r j flown by an aircraft we will consider the associate set of alternatives according the links belonging to such route. We will note such alternatives by:

$$Alt(r_j) = \prod_{k=1}^{k=L(r_j)}$$

where $L(r_j)$is the number of links of route r_j having alternatives choices. For each aircraft involved in the simulation one has to choose optimal route and speed in order to avoid conflicts and to insure wake turbulence separation in the terminal area.

Depending on the route used, aircraft may have more or less options for the path planning. For instance (see Figure 5-3), an aircraft entering entry point 1 has alternative choices only on link (1;5) but an aircraft entering entry point 2 has alternative choices on links *(2;4)* and *(4;5)*. So our state space X may be summarized by the following table:

$$\vec{X} = \begin{array}{|c|c|c|c|} \hline \vec{a}_1 & \vec{a}_2 & \dots & \vec{a}_{|\mathcal{F}|} \\ \hline v_1 & v_2 & \dots & v_{|\mathcal{F}|} \\ \hline \end{array}$$

where *ai* is the vector of alternatives of flight *fi* and *vi* is the associated speed. It must be noted that dimensions of vectors *ai* may differ according to the routes used by the aircraft.

We are searching a point in this state space which minimizes the total number of conflicts:

1. Wake turbulence "conflict" : $\forall f_i, f_j \in \mathcal{F}$ flying on the same link and for which fi is the leader, $d(f_i, f_j) > s_{ij}\ \forall t \in [0, T]$, where $d(f_i, f_j)$ is the distance separating aircraft $\boldsymbol{f_i}$; $\boldsymbol{f_j}$; $\boldsymbol{s_{ij}}$; is the separation standard which depends on the aircraft's wake turbulence category.

2. Conflicts on node : when an aircraft *fi* is flying over a node *nk*, other aircraft have to be 5NM away from the node.

This optimization process is subject to the following constraint :

- Speed constraint : 8 fi 2 F vi 2 [vi_{min} ;vi_{max}]

Having discrete and continuous decision variables such problem belongs to the class of mix optimization problems.

The combinatoric associated to the discrete part can be summarized by the following formula :

$$|X| = \prod_{i=1}^{i=|\mathcal{F}|} \prod_{k=1}^{k=L(r_i)} alt(l_k)$$

For instance, for 50 aircraft with an average number of alternatives equal to 5, the induce combinatoric is about 5^{50}. Furthermore, the objective function is non linear, not convex and not separable. The state space is not connected meaning that deterministic optimization approach are not suitable for such problem. This problem is NP-Hard. We have then developed a stochastic approach based on evolutionary algorithms which are detailed in the next section.

5.5 Evolutionary Algorithms

Evolutionary algorithms use techniques inspired by evolutionary biology such as inheritance, mutation, natural selection, and recombination (or crossover) to find approximate solutions to optimization problems [12], [19], [16], [22]. An individual, or solution to the problem to be solved, is represented by a list of parameters, called chromosome or genome. Initially several such individuals are randomly generated to form the first initial population (*POP(k)* on Figure 5-4).

Then each individual is evaluated, and a value of fitness is returned by a fitness function. This initial population undergo a selection process which identify the most adapted individual. The one which has been used in our experiments is a deterministic (λ;μ)-tournament selection. This selection begins by randomly selecting individuals from the current population (*POP(k)* and keeps the μ bests (λ>μ). This two steps are repeated until a new intermediate population (*POPi*) is completed. Following selection, one of the three following operators is applied : nothing, crossover, and mutation. The associated probability of application are respectively:

$$(1 - p_c - p_m)),\ p_c \text{ and } p_m.$$

Crossover results in two new child chromosomes, which are added to the next generation population. The chromosomes of the parents are mixed during crossover. These processes ultimately result in the next generation population of chromosomes (*POP(k+1)* on Figure 5-4) that is different from the initial generation. This generational process is repeated until a termination condition has been reached. The next section presents the application of EA to our problem.

The first step consists in the selection of the best individuals from population POP(k). Afterward, recombination operators are applied in order to produce the POP(k+1) population.

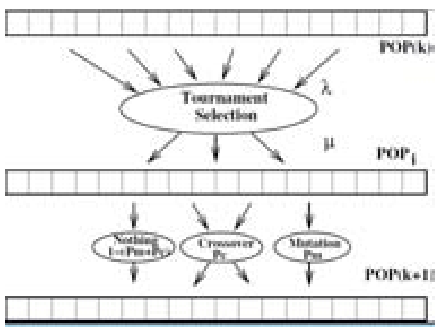

Figure 5-4: Genetic Algorithm with Tournament Selection.

5.6 Application to our problems

5.6.1 CODING

In order to make run the GA on such problem, one first has to design an efficient coding easily managed by recombination operators. We first consider the set of aircraft involved in a given time window for which one want to optimize the merging and sequencing for landing. For each aircraft, one has to find an optimal route and some speed regulations. The coding is then summarized by a table which gather together all the decisions variable for all the aircraft involved in the time window (see Figure 5-5). The chromosome consists in two parts. The first part is link to the speed changes (blue) and the second one describes the alternatives route for a given aircraft. Depending of the entry point, aircraft may have different number of alternative. For instance, aircraft entering TMA (see Figure 5-3) by the first entry point have only one alternative but the one entering by the others point (2 and 3) have two. In order to memorize the performances of a given decision, we put an extra table which gather the number of conflicts a given aircraft has encountered on his route. This information will be used by the recombination operators in order to focus on aircraft involved in conflict.

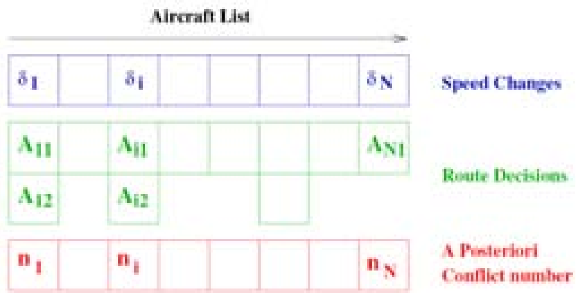

Figure 5-5: State Space coding

5.6.2 INITIALIZATION

In order to make run the Evolutionary process, one must be able to initiate a population of chromosomes. If no information about the structure of optimal solutions is available at the beginning of the optimization process, one can use a uniform random trial to initialize the population.

5.6.3 CROSSOVER

The crossover operator is a bias uniform crossover for which each gene is check in order to be put in the next generation. For each gene *i* (aircraft), we compute the summation S of conflict number in both parent *P1* and $P_2 : S = ni(P_1) + ni(P_2)$. Then, we compute the probability PC to transfer the decision variable of gene *i* in both children:

$$P_c = 1.0 - \frac{ni(P_1)}{S}$$

When there is no conflict in both parent such probability is set to ½ . Based on a uniform random trial between 0 and 1, we decide when gene from parent P1 or parent P2 is inserted into children chromosomes (see Figure 5-6).

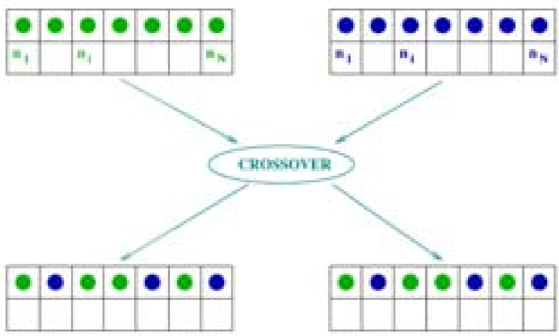

Figure 5-6: Bias Uniform Crossover.

5.6.4 MUTATION

As for the crossover operator, a bias is introduced in order to focus on aircraft involved in conflict. To do that we begin to compute the total number of conflict in the chromosome:

$$N_{conf} = \sum_{i=1}^{i=N} n_i$$

Then we generate a random number *p* between *0* and *1* (uniform distribution) and we compute the cumulative following summation :

$$S(k) = \sum_{i=1}^{i=k} \frac{n_i}{N_{conf}}$$

till *S(k) < p* for which the gene k is then mutated (see Figure 5-7). Depending of the configuration of the GA, the mutation may change the speed of an aircraft, its route or both.

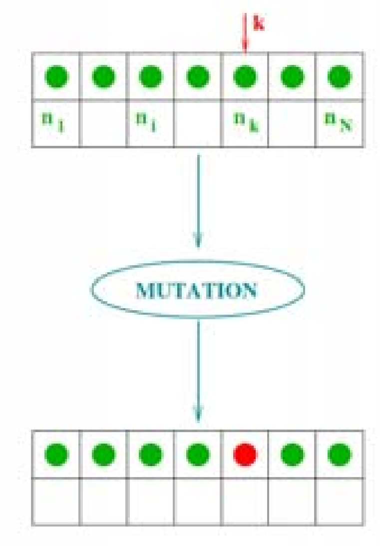

Figure 5-7: Bias Mutation.

5.6.5 FITNESS COMPUTATION

The fitness computation is based on a simulation of the traffic in the TMA based on the decision variables of a given individual. For each aircraft, we compute its track on the route network (nodes and links). Such track consists of a set of positions of the aircraft every 10 seconds. Those tracks are then used to compute the conflict appearing on nodes and links. This first computation represents the first objectives we have to set to zero (*y1*). Then, for a given planning, the speed changes and extra distance are computed for all aircraft in order to build the second objective *y2*. Finally, we gather together those two previous objectives into a single fitness that has to be maximized:

$$fitness = \frac{1}{0.01 + y_1} + \frac{1}{0.01 + y_2}$$

This fitness reach 200 value when both objectives *y1;y2* are equal to zero. Based on the results of such simulation, it is possible to update the conflict number for each aircraft in order to guide recombination operators.

5.7 Results

The algorithm has been tested on the Gran Canaria terminal maneuvering area (see Figure 5-2). This associated model is given on Figure 5-3for which four link have been extended with some alternative routes. Two scenarios have been investigated with 35 and 50 aircraft respectively on the same time period of 1 hour.

5.7.1 RESULTS FOR THE FIRST SCENARIO

5.7.1.1 Scenario Description

A synthetic STAR configuration of the Gran Canaria TMA has been used (as depicted in Fig. 8) to test the benefits of the proposed algorithm. In the arrival phase, three routes fuse into one single route towards the final approach (runway 03L/03R) by merging in two different waypoints. Three different routes were defined, two correspond to current STARs defined in the Spanish Aeronautical Information Publication (AIP), TERTO3C and RUSIK3C, and one additional STAR was defined in order to complicate the traffic flow in the scenario presented. This last STAR is defined by the name NPWT3C. The waypoints sequence for each of the three STARs is as follows:

- TERTO3C: TERTO, LZR, BETAN, CANIS, ENETA (IAF), LPC (FAF), RWY
- RUSIK3C: RUSIK, FTV, FAYTA, CANIS, ENETA (IAF), LPC (FAF), RWY
- NWPT3C: NWPT, FAYTA, CANIS, ENETA (IAF), LPC (FAF), RWY

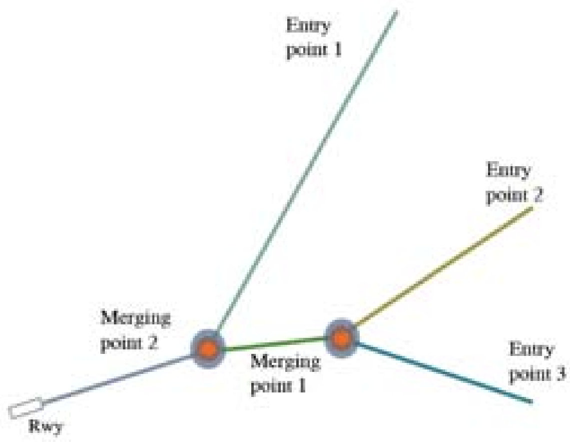

Figure 5-8: Synthetic Gran Canaria STAR

The algorithm is designed to solve detected conflicts in an horizon between TMA entry point to the initial approach fix (IAF) point by amending either the speed or the trajectory of the aircraft such that the conflict is solved, no new or secondary conflicts are produced, and the aircraft accomplish its original required arrival time.

The GA parameters used for the first scenario are the following:

Pop size	100
Number of generation	20
Probability of Crossover	0.3
Probability of Mutation	0.3

The Figure 5-9 show the evolution of the fitness features with generation.

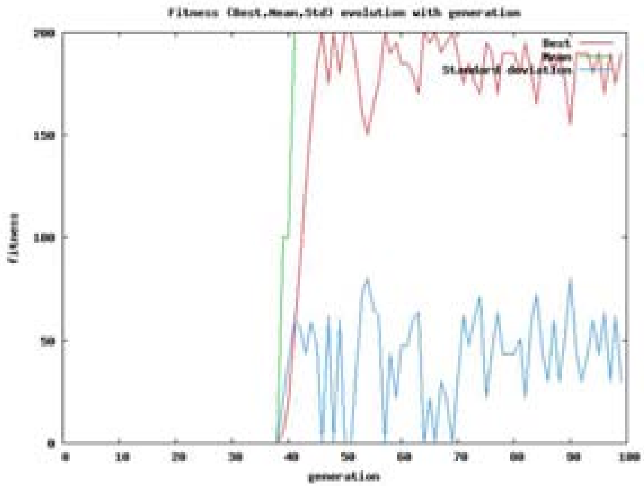

Figure 5-9: Evolution of the best fitness; average finess and standard deviation of the best individual with generations

The experiment has been done on a 3Ghz Pc based on a Java code. The evolution of the fitness features are summarized on Figure 5-9 for which the fitness of the best individual, the average fitness on population and the standard deviation are plot with generations. As it can be seen on Figure 5-9 the EA (Evolution Algorithm) find an optimal solution (*y1 =y2 =0, fit =200*) solution after 42 generations.

The associated evolution of criteria is given on Figure 5-10. The conflicts on links are first eliminated after 10 generation and conflicts on nodes disappear after generation 42.

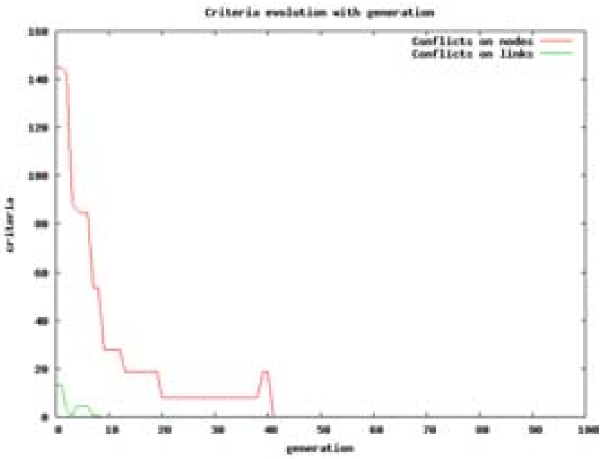

Figure 5-10: Evolution of criteria y1,y2 with generations for the first scenario

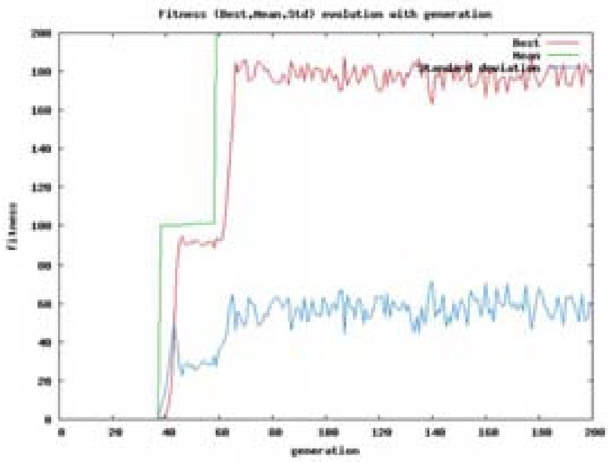

Figure 5-11: Evolution of the best fitness; average fitness and standard deviation of the best individual with generations

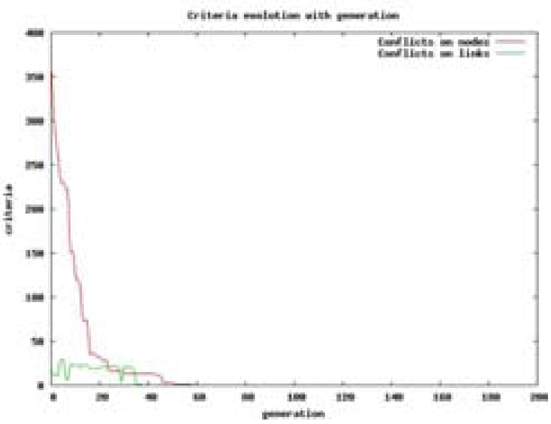

Figure 5-12: Evolution of criteria with generations for the second scenario

5.7.2 RESULTS FOR THE SECOND SCENARIO

Having more aircraft in this scenario, the EA parameters setting are not suitable anymore. We change in the following way in order to find optimal solutions:

Pop size	200
Number of generation	200
Probability of Crossover	0.3
Probability of Mutation	0.3

The Figure 5-11 show the evolution of the fitness features with generations. An optimal solution is found after generation 60 with a fitness equal to 200.

The associated evolution of criteria is given on Figure 5-12. As in the first experiment link conflicts disappear first and node conflict are removed after generation 60.

5.8 Conclusion

In this paper we have presented a new approach for the aircraft sequencing and merging problem in TMA. For each aircraft a new route may be selected in a discrete finite set and a new speed may be assigned.

A mathematical model has been developed for such problem with a description of the state space, constraints and objective function. A complexity analysis has shown that stochastic optimization is the most adapted approach to address such problem.

An Evolutionary Algorithm has been presented for which chromosome coding and operators have been developed.

Such algorithm has been applied to Canaria airport in Spain with real traffic demand samples. In both situations, all conflicts have been successfully removed on links and at merging points.

5.9 Acknowledgment

This research effort is partly funded by two main projects in the air traffic management domain with the aim of providing a significant contribution to the attainment of the common European goals set by the SESAR program and beyond. On is the CyCIT (TRA2008-05266/TAIR) by the Science and Innovation Ministry of the Spanish Government Discrete Event Simulation Platform to improve the flexible coordination of land/air side operations in the Terminal Manoeuvring Area (TMA) at a commercial airport; and the second project is The ATLANTIDA leaded by BR&TE together with key research companies and Spanish

universities, Universitat Autnoma de Barcelona (UAB) has been collaborating with Boeing Research and Technology Europe, ATOS-Origin and INDRA in the development of a causal model to improve CD/CR algorithms performance.

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OVERALL CONCLUSIONS AND FUTURE WORK

This PhD dissertation has been written in an article compendium format where three scientific journals papers and two conferences papers have been introduced because they have been considered as the most representative articles. The contributions of each of the case studies; overall conclusion and future research lines are addressed in the last section of each Chapter. The main contributions of this work are summarized in the following paragraphs.

The decision making process concerning complex systems often strains human capabilities mainly because there are plenty individual interactions among system's variables which makes difficult to predict how a system will react to an external manipulation such as a policy decision. Decision Support Systems have been gaining an increasing popularity in many domains mainly because they provide a cost-effective method to deal with the decision making process.

Although there are different approaches towards making efficient decisions, this research proposes to integrate a common framework for modelling complex systems under a causal approximation to tackle the decision making process. In this regard, diverse case studies have been analysed in the manufacturing and transportation industry, in both land and air operations to validate the objective. The proposed causal modelling technique has been applied to complex timed and untimed problems such as the Pallet Loading Problem, and the Conflict Detection & Conflict Resolution problem in the Air Traffic Management field.

It is proposed to exploit the advantages of a Discrete Event Systems approach for reaching efficient solutions in the performance of operations due to their capability of generating feasible solutions supported by a quantitative analysis of the system. A Discrete Even System can be described as a dynamic system whose behaviour can be represented by discrete state variables and is governed by asynchronous and instantaneous incidences, called events, which are solely responsible for the state changes. The DES approximation allows the generation of the sequence of events or activities that should take place within a system, to reach a certain final state while minimizing a certain cost function.

The Coloured Petri Nets formalism is broadly used to model DES due to its capability to capture the cause-and-effect relationship between different system states, formalizing in this way the knowledge of the system. CPNs also support information flows which are critical in any logistic or production decision making activity.

CPN also offers the possibility to use simulation and the state space analysis technique to understand the behaviour of the system. This is one the main advantages to exploit since it can bring a deep knowledge concerning the events that take place and their interactions which is essential to remove non-effective operations, avoid delay propagation up and down stream and improve the solutions for an efficient decision making process. From a constructed state space, it is possible to answer a large set of verification questions concerning the behaviour of the system, such as absence of deadlocks, the possibility of always being able to reach a given state, and the guaranteed delivery of a given service, among others.

Moreover, this methodology allows the development of heuristics based on the system's behaviour, incorporating the expertise gained from the analysis of the system to generate new and more efficient constraints that will decisively reduce the computational time needed to explore the state space. In the case study presented in Chapter 4 concerning the palletizing problem, diverse heuristics for the box placement have been developed. This has achieved excellent results, even better that commercial software, providing more space utilization to load a pallet which minimize the time of the loading process. Diverse advantages can be reached if the process time to fulfil pallets is minimized such as improving the whole transport operations in a supply chain operation which brings along an important cost benefit for the whole manufacturing industry.

On the other hand, by performing simulations of the model, it is also possible to investigate different scenarios and explore the behaviour of the system. Very often, the goal of performing simulations is to debug and investigate the system design. Hence, simulation of complex systems is advantageous for behavioural analysis when the real systems cannot be used to analyse nor the state space is possible to be fully constructed. These characteristics are particularly relevant when working in practical industrial problems such as the Air Traffic Management in the transportation industry. The Terminal Manoeuvre Area case study analysed in Chapter 3 provides the necessary evidence that a deep knowledge of the events and their interactions in a TMA is essential to remove non-effective operations, avoid delay propagation between arrivals and optimise the occupancy of the runway. The Terminal Manoeuvre Area is a very special airspace sector designed to handle aircraft arriving to and departing from airports and hence any improvement in the TMA can achieve important benefits for the overall Air traffic Management operations. In this regard, some improvements can be pointed out from the works introduced in Chapter 3 and 5 and Annex A The causal model developed proposes an innovative landing procedure, where different alternative pre-defined segments are allowed for each flight to land.

The proper management of 4D trajectory allows to integrate more tightly strategic and tactical operations in order to improve air traffic operations, in particular to increase the overall predictability of traffic, with very important cost-benefit to airlines and to the Air Traffic Management system. In this regard, EUROCONTROL and the SESAR (Single European Sky ATM Research) programme are dealing with diverse concepts to have an affordable, seamless system of ATM, enabling all categories of airspace users to conduct their operation with minimum restrictions and maximum flexibility while meeting or exceeding the measurable targets for safety, operational efficiency, and cost effectiveness requirements.

Chapter 5 presents other novel approach also under the SESAR context for merging multiple aircraft flows in a Terminal Manoeuvring Area. This approach optimizes a set of aircraft planned to land at a given airport which is proposed to merge the incoming flows from different routes by mean of speed and path changes. An optimization algorithm has been developed in order to propose to each aircraft a new route and speed profile for which conflict free flow merging is produced smoothly with optimal runway feeding. Meta-heuristics are able to cope with complex problems of combinatorial optimisation. The optimisation problem presented in this paper can also be used as a decision support tool to deal with other innovative procedure for landing which is essential to assess the overall efficiency of the ATM.

In the Annex A, the development of a decision support algorithm to tackle the merging and sequencing problem within the Terminal Manoeuvre Area sector is proposed. A flexible terminal area route structure is analysed together with a first come first serve sequence policy. Later on, the sequence has been altered by means of the Constrained Position Shifting method which essentially shifts the position of the aircraft in a queue prior converging on to the final approach. The improvements expected are: increase throughput by enabling reduced separation, more effective sequencing, parallel approaches and flexible arrival and departure routes, throughput, decreasing delay, and ensuring fairness can be effectively modelled, among other. Further work can be implemented to include general cost functions and to mix arrival and departure operations, including the merging of multiple departure queues.

Therefore, the case studies presented in this research justifies that a causal modelling approach aim in the correct direction to serve as the basis for developing more efficient decision support tools to be implemented in the transportation industry, specially to improve the current ATM system. The integration of these DSS enables extensive application of diverse procedures for arrivals in terminal airspace even at high traffic loads conditions– in contrast to the currently prevalent methodologies available for ATM purposes.

This causal modelling approximation also propitiates the more widespread use of DSS into the transportation field to enhance the management of operations during busy traffic periods. In addition, it is not only expected to bring a range of benefits on its own, but it is also considered as a sound foundation for the SESAR concepts.

The developed models generate optimal solutions of industrial systems in an efficient way making use of the causal modelling approach. In this context, diverse further work can be done by exploiting this characteristic to enhance the causal modelling scope to incorporate economic variables, as for example fuel consumption aspects in the ATM problems. When incorporating these variables, it is possible to design a cost function that would be minimized by using an algorithm, meta-heuristic or other searching or reduction technique, or both to explore the coverability tree associated with the causal model.

As a matter of fact, some of this implementations are currently under development, but unfortunately due to time limitations and the amplitude of the field, this research has provide only the most representative case studies.

The causal models are being used to get insights of the en-route capacity problem, where, according to future SESAR targets, all users must benefit from increased flexibility by providing capacity headroom where possible and by developing techniques that will enable resources to be deployed in response to accurate real-time demand information. Hence, causal models have the advantage of gaining knowledge of diverse scenarios, to effectively explore diverse trade-offs in managed airspace, particularly in en-route, where user preferred trajectory will apply without the need to adhere to a fixed route structure. The model contributes in a variety of planning purposes, such as computing the total cost or delay per flight in diverse traffic scenarios; or assigning different service priorities rules or metrics, and to perform a sensitivity analysis of the delays and costs induced respect to changes in the shared business trajectory. Other important factors that can be analysed are the impact of the network geometry, characteristics of the service demand, or criteria for assigning priorities to particular flights when the service rule has been chosen.

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6 ANNEX A: CAUSAL MODEL TO SEQUENCE AND MERGE 4DT FLOWS IN TMA

Abstract

It is well accepted by ATM community the necessity to integrate more tightly strategic and tactical operations in order to increase throughput by enabling reduced separation, more effective sequencing, parallel approaches and flexible arrival and departure routes, among other. This integration has been analyzed and it is expected to be solved by different ATM modernization projects, mainly through a wide system information management by taking advantage of the continuous technological improvements on aircraft instrumentation, communication systems, advanced automation tools, collaborative decision-making processes, among others. In this sense Europe and the United States government and private organizations have been developing plans for future Air Traffic Management (ATM) systems to work out on the demand forecast for the years 2020 which is expected to result in a doubling of aircraft movements when compared to those in 1998.

This abstract summarizes the development of a decision support algorithm to tackle the merging and sequencing problem within the Terminal Manoeuvring Area (TMA) sector. The algorithm works with multiple landing traffic flows that share the airspace in the same time window. A flexible terminal area route structure is proposed; it eliminates conflicts within the Standard Terminal Arrival (STAR) while traffic is merged prior converging on to the final approach. As a first instance the first come first serve (FCFS) sequence policy will be tasted and later on the sequence will be altered by means of the Constrained Position Shifting (CPS) algorithm. Gran Canaria STAR is used to evaluate the benefits of the proposed model under synthetic traffic; and to determine the spacing buffers the ICAO Separation minima (ICAO DOC-4444) criteria is used as on current methodology.

6.1 Introduction

The Terminal Manoeuvring Area which is perhaps, the most complex type of airspace, needs special attention when dealing with the integration of strategic and tactical operations. There has been pointed out the necessity to integrate related TMA operations into the overall ATM organization. Congested TMA are being forced to accept more flights each day, and departure pushes to accommodate late arriving flights causing further up & down-line disruptions. Therefore, it is inevitable to demand tools for an efficient TMA air traffic control procedure, such as, landing and departing operations are scheduled maintaining separation between aircraft which minimize the deviation between desired and conflict free trajectory for each aircraft.

For each scheduled proposed, it is important to have a smooth flow of arriving traffic as there are fewer options that can be used to control multiple inbound flows with-out too much interference among aircraft. This requires an early planning of the arrival traffic and the early and reliable co-ordination of expected/required arrival times between arriving aircraft and ATC (particularly with the Arrival Management tool, AMAN). Today, Precision Area Navigation (P-RNAV) arrival procedures have been defined in the vicinity of some European airports, aiming at airspace capacity, workload, efficiency, predictability and/or environment-related benefits. These procedures have been designed with the goal of replacing open-loop vectors in Approach for arrivals, and allowing revisiting associated working methods. This procedures enable equipped aircraft to self-navigate from point to point, it is workload intensive for the controllers to efficiently merge aircraft from different directions using mixed operating procedures [11] [21].

Area Navigation (RNAV) is a method of Instrument Flight Rules (IFR) navigation that allows an aircraft to choose any course within a network of navigation beacons, rather than navigating directly to and from the beacons. This can conserve flight distance, reduce congestion, and allow flights into airports without beacons. RNAV can be defined as a method of navigation that permits aircraft operation on any desired course within the coverage of station-referenced navigation signals or within the limits of a self-contained system capability, or a combination of these. In this work, it is assumed that all aircraft are fully equipped and can follow RNAV procedures.

The improvement in aircraft capabilities such as the Flight Management System (FMS)/autopilot-coupled, aid aircraft to be able to fly Required Navigation Performance (RNP) achieving accurately their desired horizontal paths and flying efficient Continuous Descent Approaches (CDA) from cruise altitudes to touchdown.

The procedures described in this paper are concerned with the arrival phase of flights, typically starting when aircraft leave their cruise level in En-Route – having reached their Top of Descent (TOD), and ending when aircraft reach the Final Approach Fix (FAF) or are transferred to the Tower as stated in the work of [11]. This phase can be split into Terminal Manoeuvring Area phase and Approach control phase. In this work it is also introduced the notion of an Extended Terminal Area (E-TMA) to handle high-density airspace dealing with traffic inbound to one or several major airport(s). E-TMA could be considered as a transition between En-Route and TMA sectors, generally corresponding to delegated airspace from En-Route and covering the control phase of flights that are already in descent – or about to start descent, leaving the En-Route network – but have not entered the TMA yet (see Figure 1).

Current sequence and air traffic control operations start even before an aircraft takeoff. Aircraft navigate over established Standard Terminal Arrival Route (STAR) from the meter fixes to about 10 to 15 nm radial distance from the airport. In this area, the integration of aircraft flows essentially relies on the use of open loop radar vectors (heading instructions). Controllers must recognize and select the proper technique by which they can alter an aircraft's position within a flow, if it is intended to, or, solve potential conflicts by spacing aircraft in his sector. This control would be extended to include a complete lateral path to the final approach course, plus a vertical profile (speed and altitude), all of which become part of the arrival clearance. Although this method is efficient and flexible, it is highly demanding for air and ground sides under high traffic load conditions, as it imposes rapid decisions for the controller and time-critical execution by the flight crew. The air traffic control operations diverge from one day to another and their main purpose are to avoid dangerous encounters instead of optimizing the landing sequence.

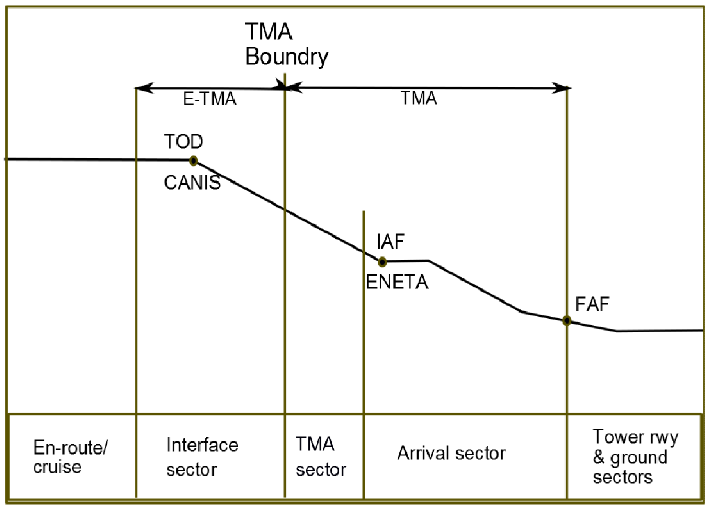


Figure 6-1: Organization of the arrival phase of flight

In the approaching phase, the present work deals with the landing sequence problem that arises from operational and fairness considerations by means of the Constrained Position Shifting (CPS) method. Dear (1976) recognized that, in the short term, it is unrealistic to allow arbitrary deviations from the FCFS sequence for two reasons:

- the system affords controllers limited flexibility in reordering aircraft, and
- large deviations from a nominal schedule may be unacceptable to airlines from a fairness standpoint.

This observation led to the CPS approach for scheduling aircraft, which stipulates that an aircraft may be moved up to a specified maximum number of positions from its FCFS order.

The CPS method states that an aircraft's position in the sequence should not deviate significantly from its position in the FCFS sequence. In the work proposed first by [9], it is stipulated that an aircraft may be moved up to a specified number of positions where the parameter *k* is the resulting maximum number of positions allowed to change called k-CPS scenario. For example, we assume that the aircraft are labelled *(1,2,…,n)*, according to their position in the FCFS sequence. The network consists of ***n*** stages *{1,…,n}*, where each stage corresponds to an aircraft position in the final sequence; in a 2-CPS, an aircraft that is in the 22nd position in the FCFS order can be place at the 20th, 21st, 22nd, 23rd and 24th position in the new order.

An additional advantage of using CPS is that it maintains some sense of equity among the aircraft by not deviating too much from the FCFS order. It also helps to maintain a sense of fairness in the perception of the airlines that operate the aircraft. Our study includes a heuristic method subject to a single position shift (i.e. 1-CPS).

The remainder of this paper is structured as follows: Section II presents the related works in the field of CD and CR methods, TMA, flow merging and integration, RNAV procedures. In Section III encloses the problem description as well as some general assumptions made for the model. Section IV presents the principles behind CPN as well as the codification of the CPS and CD&CR algorithm in the CPN syntax. Conclusions and future works are discussed at the end of the paper.

6.2 Previous work

A search of the literature in three main areas was conducted to identify concepts related to treating terminal merges and sequence problems. First literature was concerning about conflict detection and resolution algorithms; Secondly literature concerning merging/integrating flows, RNAV procedures and terminal manoeuvring area (TMA) routes called SID and START. ; Finally the third search was about different algorithms for the landing sequence problem. This search yielded different bibliography addressing these topics but none had the same problem context that is being investigated here.

6.2.1 CONFLICT DETECTION AND RESOLUTION (CD&CR)

In the last decades different researchers have been studying the evolution of air traffic and have been designing CD/CR tools to improve ATM performance. Most proposed solutions have been exercised through a set of scripted, controlled or simplified scenarios and algorithms are focused mainly in the en-Route phase.

To begin with, an overview of important considerations for the CD and CR problem has been provided by [20] where over 60 different methods have been analyzed and classified.

Some of the methods presented are currently in use or under operational evaluation for example the user interface of T-CAS as in [26] or CTAS developed by NASA Ames Research Centre. Centre/TRACON Automation System (CTAS) is a suite of air traffic decision support tools. Two of these tools have been implemented, tested and included in the FAA Free Flight Phase One deployment plan: the Traffic Management Advisor and the passive Final Approach Spacing Tool (pFAST). The Traffic Management Advisor provides an efficient schedule for arrival aircraft entering congested terminal areas. This provides resolution advisories (flight level changes) to pilots involved in two aircraft conflict. Its main disadvantage is it usually considers separation only at the schedule location; it does not consider separation at other points along the trajectory.

FACES (Free-Flight Autonomous Coordinated En route Solver) is a model for coordinated on-board sequential conflict solving presented in [1].

Some of the different CD and CR algorithmic approaches that have been investigated are: linear programming as in [23], Genetic Algorithms from [3], Stochastic Optimization as in [24], Evolutionary Computation from [18], Geometric Algorithms such as the work of [8], Ant Colony Optimization from [10] Semi-definite Programming as in [14], among others.

6.2.2 MERGING/INTEGRATING FLOWS AND RNAV PROCEDURE

Previous work related to traditional routes, RNAV routes and procedures can be found in [6], [11], [12] and [19]. In the work of [16] and [15] RNAV routes considered in the terminal area but the routes did not merge. In the last three works previously cited the use of airborne spacing in the TMA where investigated At the EUROCONTROL Experimental Centre, a specific method called point merge technique has been identified, along with its associated route structure. The method proposed it’s said to be usable without airborne spacing. It enables integrating flows in the terminal area through systematic procedures without relying on open loop radar vectoring. The principle is to achieve the aircraft sequence on a point (with conventional direct-to instructions) using predefined legs at iso-distance to this point for path shortening or path stretching. Except RNAV capabilities, no specific airborne functions or ground tools are required.

6.2.3 LANDING SEQUENCE PROBLEM

Within the literature there have been different approaches for the landing sequence problem; the ones based on Linear Programming such as [4] which solves the static case presenting a mixed-integer zero-one formulation of the problem together with a population heuristic algorithm; Dynamic-Programming-based approach which used a method called CPS as in [7] and [22] for the static case and [3] and [7] where a first class of algorithms are presented that are able to handle commonly encountered operational constraints (as also in [5]) and objectives within the CPS framework The heuristic algorithm developed (a population heuristic).

Another kind of approaches are based on computational intelligence as in [15] where Genetic Algorithms (GAs) are used; Different hybrid algorithm are also been proposed as in [17] where the Clonal Selection Algorithm is designed to schedule aircraft in current receding horizon, and then Receding Horizon Control repeats the optimizing procedure until all aircraft have landed; another example of an hybrid algorithm is proposed by [13], this approach is based on the Artificial Fish School algorithm combined with GA and SA algorithm.

6.3 Problem Definition

Although different approaches have been introduced in the previous section for the CD&CR, the sequence and merging problem, most proposed solutions cannot deal with the three concepts together. As said in [24] a deep knowledge about all the events that take place and their interactions is important. Therefore, this work integrates the CPS algorithm to manage sequence problem while applying a causal model to merge, predict and solve conflicts within TMA trajectories. This research develops a simulation model, first to help the scheduling decision activity in the landing sequence when dealing with other than the FCFS sequence and secondly to merge arrival flows properly separated even in a share mode (mixing arrivals and departures) and providing a feasible runway makespan.

In this context, it is possible to understand the system dynamics from a discrete event system approach, in which each operation has a certain number of preconditions, duration time estimation, and a set of post conditions (changes in the state of airport information).

The merging of arrival flows into a single runway sequence in current day operations is often performed through the use of open-loop vectoring. In case of traffic peaks, ATC typically issue a large number of heading, speed and FL/Altitude tactical instructions. This method is highly flexible; however it presents some other disadvantages such as intensive use of the Radio Telephony (R/T), and hence inefficiency in system involving trajectory prediction (e.g. conflict detection tools, AMAN) that cannot be updated appropriately since the time and location of aircraft is not known in advance, among other factors.

Present research consists of a new approach on arrival operations where a technique called “path shortening-path stretching technique” is used to coordinate the merging of multiple inbound streams. As a result new conflict free 4DT’s are generated in the TMA preserving the safety distances in the runway threshold.

Two concepts are important to define in this section:

Default Minima: The separation minima specify the default minimum separation required between two aircraft and are called separation standards. This is regulated by the International Civil Aviation Organization (ICAO); For terminal areas surrounding of most major airports, the minimum lateral separation is 3nmi and Table I shows the vertical separations criteria used which take into account the category of the leading and the following aircraft.

Conflict detection concept: The algorithm role in the conflict detection phase is to predict if two aircraft will violate required separation: either spatial (3D) or temporal. An aircraft is said to be in conflict if at least one of these separations standards is violated. Wake Turbulence Separation Application: The required wake turbulence separation depends on the weight class of the aircraft (refer to Reference ICAO DOC-4444).

The approach proposed in this work is based on a discrete event model using Coloured Petri Net (CPN) algorithm for merging and sequencing arrival flows of aircraft. The model deals with procedures as the Point Merge technique, in particular by the denoted Point Merge System [6], [11] and [12] but adds the Control Positioning Shifting algorithm to sequence aircraft. One of the most important similarities between Point Merge technique and this approach is that the conflict resolution strategy relies on the introduction of a route structure consisting of merge points and segments called "legs” or “links" where the technique to stretch/short distance to be flown is applied. The algorithm detects conflicts in a horizon between TMA entry points to the initial approach fix (IAF) point and resolves the conflict by amending either the speed or the trajectory of the aircraft. As output of the algorithm, a new set of conflict free trajectories are found where the estimations of the velocity and position vectors of aircraft can be found. These trajectories ensure the spacing among aircraft while speeds profiles and turning angles are respected.

This work deals with two main goals: The first is merging flows while avoiding potential conflicts among aircraft (conflict detection and resolution phase). For this phase, conflicts are expressed in terms of a time-based separation criterion, according to the type and sequence of an aircraft (heavy/medium/light) and is described in ICAO DOC and addressed as minimum separation standard (MSS). This level of minimum safe separation may depend on the density of air traffic and the region of the airspace, or another factors (see Table I).

Table 6-1: Separation minima [NM] (ICAO DOC-4444)

Leading	***Following***		
	Heavy	***Medium***	***Light***
Heavy	***4***	***5***	***6***
Medium	***3***	***3***	***4***
Light	***3***	***3***	***3***

The second goal is to test behaviour of the set of aircraft while applying the Control Positioning shifting algorithm to the same model. The challenge lies in simultaneously achieving safety, efficiency, and equity, which are often competing objectives.

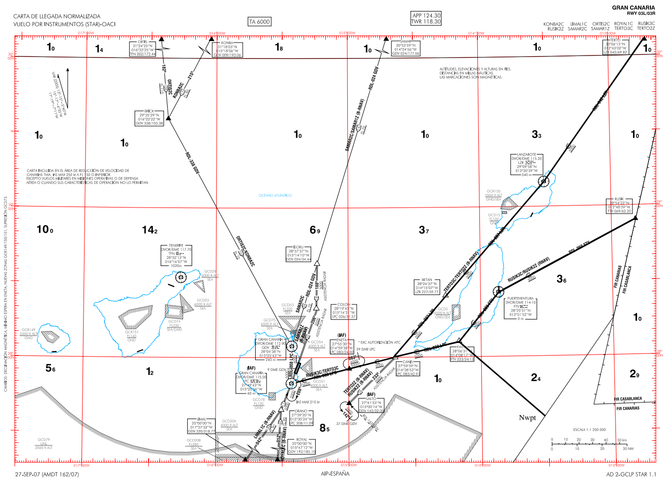


Figure 6-2: Gran Canaria synthetic STAR configuration.

A synthetic STAR configuration of the Gran Canaria TMA has been used (as depicted in Figure 2) to test the benefits of the proposed algorithm. In this STAR a new entry point (called NWP) has been added to easily generate conflicts. Figure 2 highlights the three approaching routes towards a single landing runway. These routes must fuse into one route by joining in two different merging points. An aircraft can approach by the entry point 2 (RUSIK) or entry point 3 (NWPT) and merge into one single route at merging point 1 (FAYTA); or it can approach by the entry point 1 (TERTO) and finally fuses again in merge point 2 (CANIS) with the flow coming by merging point 1 and merging point 2. It can be notice that four different 'segments or links' are formed: from entry point 1 to merging point 2; from entry point 2 to merging point 1; from entry point 3 to merging point 1and finally from merging point 1 to merging point 2.

It is important to note that the new expected arrival time is computed since aircraft enter TMA i.e. when each aircraft arrive at its corresponding merging point, and thus, control actions will be performed by the following aircraft in a look a head perspective at entry point for each particular aircraft. Control actions are used as coordination actions performed by the trailing aircraft in the form of manoeuvres which are finite sequences of flight modes such as heading and speed changes for each aircraft. These types of manoeuvres are routinely used in current Air Traffic Control practice since they are easily understandable by pilots as well as easily implementable by on-board autopilots which regulate the aircraft to heading and speed waypoints

A new merging and sequencing algorithm that considers only one single runway shared mode configuration based on CPS method and the Path shortening/Path stretching technique has been implemented. The algorithm accounts for various operational considerations (including time window restrictions and precedence constraints). The objective of this technique is to enlarge/shorten distance to be flown from the merging point to the merging point so aircraft avoid conflicts maintaining its original speed profile, if possible. As a result, a delay (dt) must be applied to the original trajectory to avoid conflicts generating an alternative trajectory, or if it is possible a new speed profile. Hence, this technique can also be seen as a delay compensated solution. It avoids the conflict by combining a heading change with a speed change in such a way that the delay introduced by the path stretching technique generates a new trajectory.

The algorithm considers three different manoeuvres to generate conflict-free 4DT's:

- Aircraft is allowed to change speed but the direction of motion remains fixed. This case is called the velocity change problem (VC problem or speed regulation);
- Aircraft fly at the same speed and it is only allowed to change instantaneously the direction of flight. This case is called the heading angle change problem (HAC problem or also called path shortening/Path stretching technique).
- The mix of both HAC and VC problem.

The proposed trajectory configuration is depicted in Figure 3 where each original route has attached a set of alternative trajectories that can be flown if a delay must be applied to avoid conflicts. Notice that even if alternatives trajectories are proposed within a segment aircraft is still passing for the same merging points and after the last merging point there is no change of path.

The operational context of the proposed causal model assumes to work with fully equipped aircraft and therefore, proposed conflict free trajectories are executed perfectly, no data-link transmission delays, nor pilot-action delays. It takes for granted that aircraft are assumed to fly highest and lowest permissible speeds over each flight link and within a fixed altitude layer until the Top of descend, TOD (see Figure 1). The model does not take into account the time to execute state changes. It is assumed that deviations are small, and the time to complete any manoeuvre change is small in comparison to the time until conflict. The arrival traffic sequence is assumed to have been determined upstream in the extended TMA by an arrival manager (AMAN) or in a FCFS policy and is conflict free when entering at TMA. Therefore sequencing is implicitly defined in the traffic preparation input file.

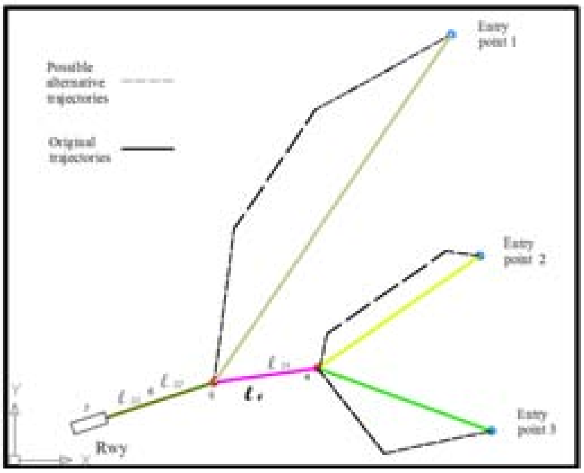


Figure 6-3: Set of alternative trajectories.

6.4 Coloured Petri Net Optimization Approach

Coloured Petri Nets (CPN) have proved to be successful tools for modelling complex systems due to several advantages such as the conciseness of embodying both the static structure and the dynamics, the availability of the mathematical analysis techniques, and its graphical nature.

The main CPN components that fulfill the modeling requirements are:

Places: They are very useful to specify both queues and logical conditions. Graphically represented by circles.

Transitions: They represent the events of the system. Graphically represented by rectangles.

Input Arc Expressions and Guards: Are used to indicate which type of tokens can be used to fire a transition.

Output Arc Expressions: Are used to indicate the system state change that appears as a result of firing a transition.

Colour Sets: Determines the types, operations and functions that can be used by the elements of the CPN model. Token colours can be seen as entity attributes of commercial simulation software packages

State Vector: The smallest information needed to predict the events that can appear. The state vector represents the number of tokens in each place, and the colours of each token.

The Colour sets will allow the modeller to specify the entity attributes. The output arc expressions will allow specifying which actions should be coded in the event routines associated with each event (transition). The input arc expressions will allow specifying the event pre-conditions. The state vector will allow the modeller to understand why an event can appears, and consequently to introduce new pre-conditions (or remove them) in the model, or change some variable or attribute values in the event routines to disable active events.

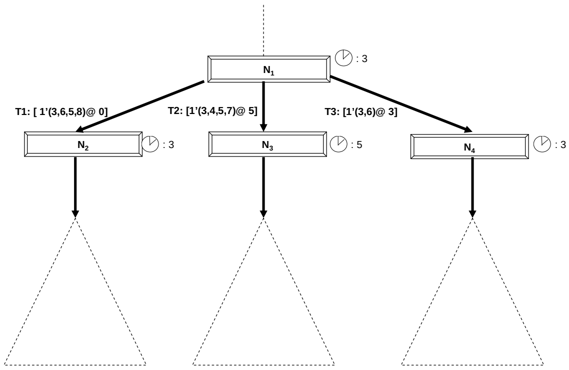


Figure 6-4: First 2 levels of a coverability tree.

From the OR point of view, the CPN model can provide with the following mathematical structures:

Variables: A variable can be identified for each colour specified in every place node.

Domains: The domains of the variables can be easily determined by enumerating all the tokens specified in the initial state.

Constraints: Can be obtained by straightforward from the arc and guard expressions. Arc expressions can contain constant values, colour variables or mathematical expressions.

From the AI point of view, the coverability tree of a CPN model allows to determine:

- All the events that could appear according to a particular system state (Figure 4).
- All the events that can set off the firing of a particular event.
- All the system states (markings) that can be reached starting from a certain initial system operating conditions M0.
- The transition sequence to be fired to drive the system from a certain initial state to a desired end-state.

The algorithm is specified in the Coloured Petri Net (CPN) formalism and is fully explain in this section. The merging and sequence problem can be seen as a discrete event system and can be integrated with the AMAN/DMAN CPN model [6] to optimize a shared mode runway in which the merging of flow arrivals is computed.

6.4.1 ALGORITHM EVENT DESCRIPTION PHASES & NET SPECIFICATION

Different phases are described into our algorithm. The first phase corresponds to the CPS method to change the aircraft sequence. The second phase is conformed by two main objectives, first the assignation of the MSS to each aircraft is model an second the generation of time windows for the HAC and VC problem. The third phase of our algorithm is in charge of the detection of vertical conflicts and a delay or idle time in each merging point is also stored. Finally the fourth phase solves potential conflicts among aircraft by means three different control actions. Indeed, let us consider these control actions as events which are represented by three different blocks of events or transitions in our CPN model:

- HAC problem; Generation of new (or alternative) routes; which is done segment by segment.

- HAC problem + VC problem; Generation of new routes + speed changes (only reduction speed is allowed in this event); which is also done segment by segment.

- VC problem; speed changes; which involves speeding up an aircraft segment by segment to avoid idle time.

Table II and Table III summarizes the most important colour and place specifications used to describe the information required, respectively.

Table 6-2: Colour specification

Colour	Meaning
acID	Aircraft identification
Gseq	Landing sequence number of leading aircraft
RN	Route to be used
Tmp	Merging point passing time
vel	Average speed
Typ	Leading type
Wv	MSS to be preserved
Dist	Distance to be flown
Tin	Entry time

Gseq2	Landing sequence number of trailing aircraft
mp	Flying by merging point identificator Mp=5 Merging point 1 Mp=4 Merging poitn 2
T1	Minimum slot time
T2	Maximum slot time
C	Ca=1 indicates that dt4 stores delay to be absorbed Ca=0 indicates that dt4 stores idle time to be absorbed
Ca	delay or idle time c=1 slot for the HAC problem (flying minimu and maximum distance) C=2 slot for the VC problem (flying minimu and maximum speed allowed)
Dt	delay or idle time

Table 6-3: Place specification

Place	Colour	Definition
Aircraft input	S	acID,Gseq,RN,Tmp,Vel,typ,WV,de,Tin
ti min, tmax	G	Gseq2,mp,t1,t2,ca
delay or idle time in Fayta	0P	Gseq,dt4,c
Solution	R	Gseq,Tmp,Vel,dist, seq,mp

First phase

The first phase of our algorithm is the implementation of CPS method. The aim of this method is the assignation of the landing sequence order of an aircraft flow which stipulates that an aircraft may be moved up to a specified maximum number of positions from its FCFS order. Figure 5 depicts the CPN for this method: In the guard expression the parameter “k” allows the CPS method to define the maximum position shift allowed while Gseq is the initial sequence order (in the FCFS) and Fseq is the final sequence to be allowed. “Aircraft input” place node has information (see Table III) regarding each aircraft trajectory such as: aircraft identification in a trajectory (acID); landing sequence number of leading aircraft (Gseq); route to be used (RN); merging point passing time (Tmp), average speed (Vel);

aircraft leading type (typ), MSS to be preserved (WV); Distance to be flown (de); and Entry time (Tin). Place “Seq and No. of ac x RN” stores the number of aircraft in each route.

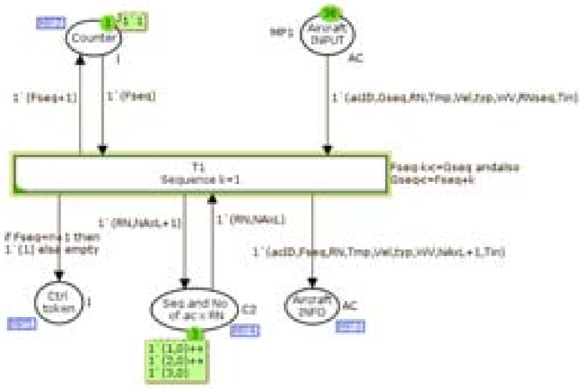


Figure 6-5: First phase: Change landing sequence (by the CPS).

For this study, the maximum position shift (MPS) allowed is k=1 that means an aircraft that is in the 5th position in the FCFS sequence (input data place) can be placed at the 4^{th}, 5^{th} and 6^{th} position in the new sequence to be solved by the CD&CR algorithm phase.

Second phase

Once an aircraft has been assigned a number in the sequence, the second phase starts by assigning the MSS considering the type of the leading and the trailing aircraft. In this same phase, two time windows are generated and this information is store in place “ti min, tmax”. One of this time windows corresponds to the slot for the HAC problem (flying minimum and maximum distance allowed from entry point to each merging point) while the second time window corresponds to the slot for the VC problem (flying minimum and maximum speed allowed from entry point to each merging point); the speed change is modified by the ±6% of average speed. Note that it is intended to absorb the delay by reducing speed (-6%vel) while flying maximum distance allowed (see Figure 6). This information is store to be used in the conflict detection and resolution phase.

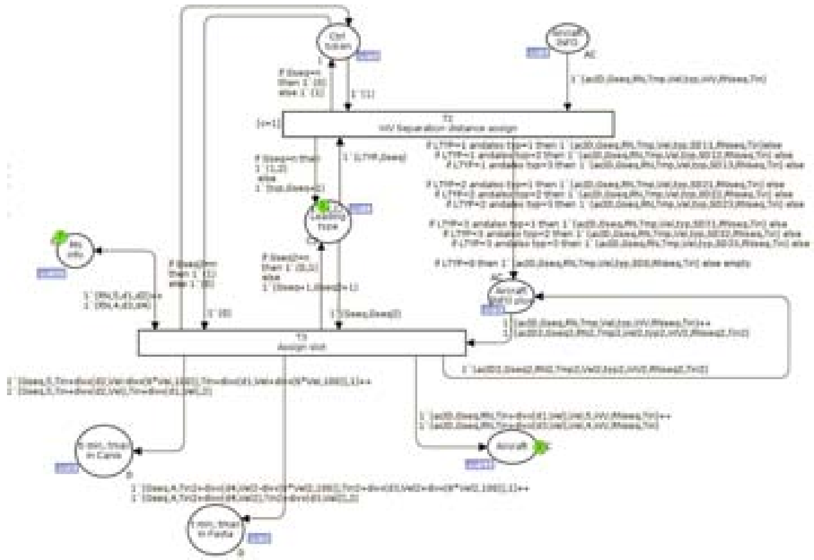


Figure 6-6: Second phase: Assign values.

Third phase

The next phase corresponds to the conflict detection phase where two situations can be predicted: an aircraft need certain amount of time to avoid conflict with the leading aircraft, and, no conflict is detected and the trailing aircraft can be speed up.

A conflict is detected is the MSS of the following aircraft is not achieved. In this case, the *delay* to be applied to the trailing aircraft so to avoid conflict is stored into the place called "delay or idle time" for each merging point (see Figure 7). In the case that no conflict is detected, the time that an aircraft can gain if it increments a 6% its average speed in each link called *idle time* is stored in the same node.

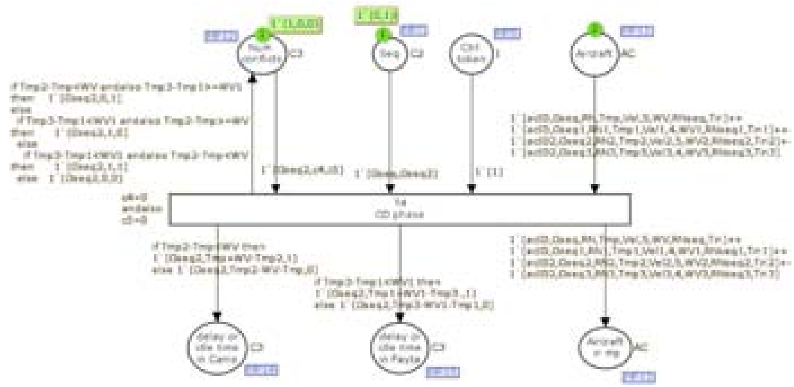


Figure 6-7: Third phase: Conflict detection.

Considering the case that one or more conflicts are detected between aircraft in the same route, the algorithm proposes the following methodology to solve conflicts:

Fourth phase

As a first instance, the HAC problem is solved by using the delay previously store to fix the passing time of the trailing aircraft so that no conflicts are generated in the other merging points. This resolution strategy is probably the most difficult to solve because it can involve the parallel resolution in other merging points.

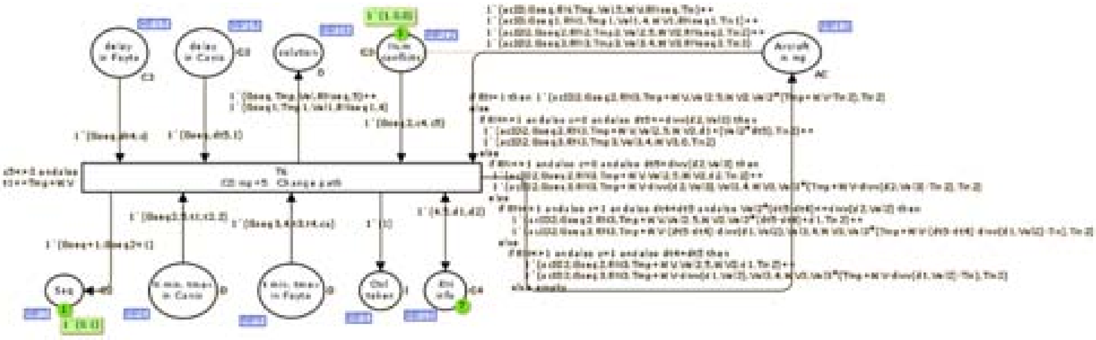


Figure 6-8: Fourth phase: Conflict resolution by HAC soltuion.

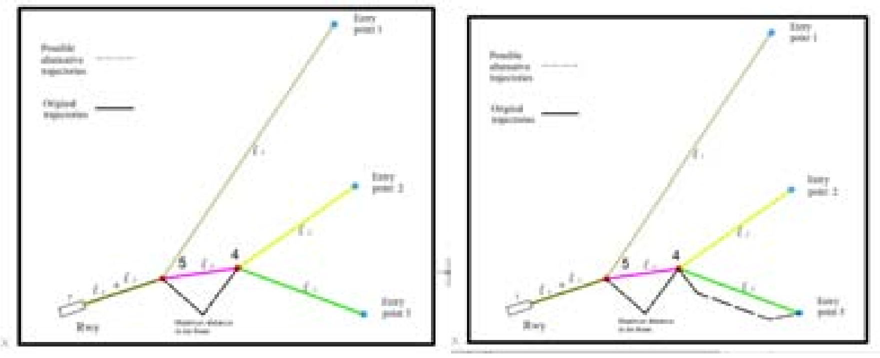
The TMA used to taste our model involves two different merging points, and hence four different events can happen in the conflict resolution phase (see Figure 8):

Option 1:

CD in merging point 1 + NO CD in merging point 2: As there is only CD in merging point 1, the algorithm intents to solve the conflict by applying the HAC solution only to the segment precedent to the conflict (in this case from waypoint 5 to 4) as shown in Figure 9a.

In case this solution does not solve the conflict because maximum path allowed is not enough to absorb the conflict then the HAC solution will be applied also the segment precedent of the merging point in conflict (in this case from waypoint 4 to entry point).

Note that most of the delay will be absorbed in the precedent link of the conflict as shown in Figure 9b and therefore only the remind magnitude will be absorbed in the precedent link. The colour dt4 will give us information about the magnitude of idle time in the precedent merging point and hence only the remind magnitude will be absorb in this segment.

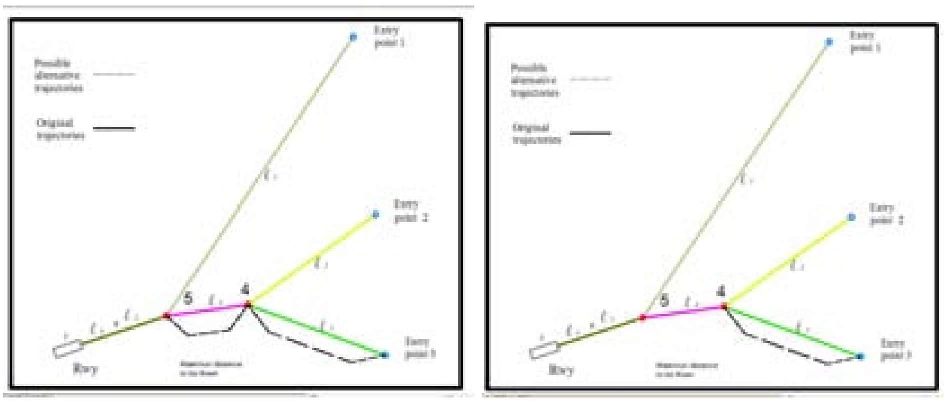


a) b)

Figure 6-9: Fourth phase: Conflict resolution by HAC soltuion.

Option 2:

CD in merging point 1 + CD in merging point 2: As there is CD in both merging points, the passing time of the trailing aircraft is fixed so as its MSS is preserved. In this case, our algorithm will intent to apply the HAC solution to the segment precedent to the first merging point in conflict (i.e. segment 4 to entry point) as shown in Figure 10a. In the case this HAC solution does not solve conflict in the successive merging point, our algorithm will intent to apply the HAC solution to both precedent segment to the merging point in conflict (i.e. segment 4 to 5 & 4 to entry point) as shown in Figure 10b.



a) b)

Figure 6-10: Option 2 by HAC soltuion.

Option 3:

NO CD in merging point 1 + CD in merging point 2: In this case, our algorithm will intent to apply the HAC solution to the segment precedent to the merging point in conflict (i.e. segment 4 to entry point) as shown in Figure 10b until the idle time in the next merging point is reach or CD is solved.

Option 4:

NO solution is possible only by HAC solution: If the conflict can not be solved only by flying maximum distance in the alternative route, then the speed is also modified. Therefore the HAC problem + VC problem are combine to solve the problem what means that the trailing aircraft will reduce its current speed until a 6% is achieved, or, the conflict has been solved (see Figure 11).

The idle time is used in the resolution phase by the VC solution to speed up and aircraft until the 6% of this current speed is reached with out generating new conflicts in other merging nodes of the route, or, until a medium speed that ensures a separation of exactly the MSS between aircraft (Figure 12).

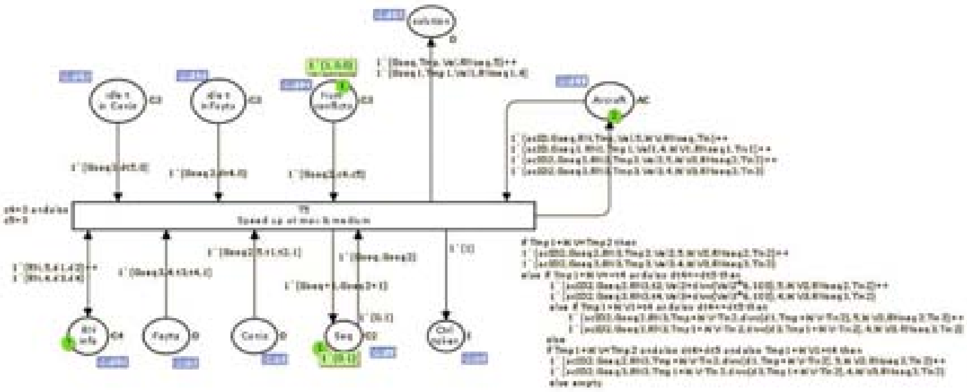


Figure 6-11: Fourth phase: Conflict resolution by VC soltuion.

After solving the conflict, Place “Solutions” store the information regarding to the aircraft successfully solved. This node contains the aircraft identification, its corresponding passing time, medium speed and total distance to be flown in each segment.

6.5 Conclusions

The present research consists of a new causal model approach on arrival operations where two main objectives are persuade; to find an optimal landing sequence that minimizes makespam while providing conflict free trajectories in the TMA sector. As future work, the model presented is going to be tasted with synthetic inbound flows using different landing sequence based on the CPS algorithm, and the “path shortening-path stretching technique” to coordinate the merging of streams. As the separation standards in TMA are lower (in magnitude) than in route, this research is expected to deal with this sort of scenarios and to lead to a deep knowledge of the cause-effect events that can result in delay into the overall ATM.

6.6 Acronyms

ATC	Air Traffic Controllers
ATM	Air Traffic Management
RNAV	Area Navigation
AMAN	Arrival Manager
CPN	Coloured Petri Net
CD	conflict detection
CR	conflict resolution
CPS	Constrained Position Shifting
CDA	Continuous Descent Approaches
DSTs	Ddecision support tools
E-TMA	Extended Terminal Area
FAF	Final Approach Fix
FCFS	Fist come First Served
FMS	Flight Management System
HAC	Heading angle change problem
IAF	Initial Approach Fix
IAF	Initial approach fix
IFR	Instrument Flight Rules
ICAO	International Civil Aviation Organization

MSS	Minimum Separation Standard
STAR	Modified Standard Terminal Approach Route
P-RNAV	Precision Area Navigation
RNP	Required Navigation Performance
TMA	Terminal Manoeuvre Area
TOD	Top of Descent
VC	Velocity change problem

6.7 Acknowledgment

This research effort is partly funded by two main projects in the air traffic management domain with the aim of providing a significant contribution to the attainment of the common European goals set by the SESAR program and beyond. On is the CyCIT (TRA2008-05266/TAIR) by the Science and Innovation Ministry of the Spanish Government "Discrete Event Simulation Platform to improve the flexible coordination of land/air side operations in the Terminal Manoeuvring Area (TMA) at a commercial airport"; and the second project is The ATLANTIDA leaded by BR&TE together with key research companies and Spanish universities, Universitat Autònoma de Barcelona (UAB) has been collaborating with Boeing Research & Technology Europe, ATOS-Origin and INDRA in the development of a causal model to improve CD/CR algorithms performance.

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7 ANNEX B: A TMA 4DT CD/CR CAUSAL MODEL BASED IN PATH SHORTENING/PATH STRETCHING TECHNIQUES

Abstract

In the present paper a discrete event model for Conflict Detection and Conflict Resolution algorithm in a TMA 4D trajectory scenario in presented which focuses mainly on the arrival phase. This arises from the overcrowding of airspace near large airports and the need to more efficiently land and take off larger numbers of aircraft. Some attempts to alleviate airspace congestion such as the reduced vertical separation minima, negotiation of voluntary reductions in scheduled service, and the construction of additional runways at major airports, have been done, however, there is still a pending matter to be solved regarding how to improve available airspace capacity avoiding non efficient procedures such as the use of holding trajectories. A deep knowledge about all the events that take place in the management of 4DT and their interactions in a TMA is essential to remove non-effective operations, to avoid delay propagation between arrivals and optimize the occupancy of the runway. The causal model developed considers different alternative pre-defined turning points for each flight evaluating path shortening/path stretching of all trajectories upwards the merging point in a TMA.

7.1 Introduction

Concerns for airspace exert a growing influence on ATM, especially around airports where airspace congestion is becoming a serious problem at many major airports and will become a more severe constraint, especially at the international hub airports serving major European cities and tourist destinations where their ATM-related operations have not yet been fully integrated into the overall ATM organization [5,7].

In the approach phase at the conventional operating methods the Air Traffic Control (ATC) further vector the aircraft to fine tune the sequence and integrate traffic flows from different Initial Approach Fixes (IAFs) to the runway axis avoiding unnecessary gaps at the runway threshold. Flexibility is without doubt one of the main characteristics of this method but unfortunately as a consequence of the strategy followed by controllers for managing arrivals in approach (with the objective of giving themselves more time and margins to make the implementation and fine tuning of the sequence easier) in high traffic load conditions, often results in high workload both for flight crews and controllers. As a consequence it is evident a difficulty to optimise vertical profiles and to contain the dispersion of trajectories. Numerous actions are required to deviate aircraft from their most direct route for path stretching and later put them back towards a waypoint (e.g. IAF) or the runway axis for integration. [2,8].

With the use of the Flight Management System (FMS)/autopilot-coupled, aircraft are able to fly Required Navigation Performance (RNP) achieving, accurately their desired horizontal paths and flying efficient Continuous Descent Approaches (CDA) from cruise altitudes to touchdown. ATC constraints and ad hoc vectoring in the airspace surrounding the airports limit the ability of these aircraft to effectively use their onboard avionics due to a lack of appropriate traffic planning [9].

An efficient landing sequence will contribute to maintaining the throughput as close as possible to the available runway capacity, ensuring optimisation of the airport manoeuvring area traffic flows and the minimisation of ground and airborne delay while conforming to the separation requirements and will also enable the more widespread use of CDAs [6]. Without an automation planning and decision support tool, it is difficult to accurately predict arrival schedules that are essential for realizing end to-end benefits of RNP for the users flying optimum paths, and for the service providers to manage traffic with varying capabilities with minimum air/ground communications [9].

An innovative technique to tackle the airspace congestion has been developed by the EUROCONTROL Experimental Centre called Point Merge [2]. The Point Merge (PM) technique aims at optimising the use of available airspace in terms of capacity, environmental aspects, and where possible in terms of track distance flown [6]. Point Merge is a structured technique for merging arrival flows derived from an earlier study on airborne spacing sequencing and merging. It is based on a specific route structure (denoted Point Merge System) that is made of a point (the merge point) with pre-defined legs (the sequencing legs) equidistant from this point for path stretching/shortening [10].

In response to the need for an alternative model to build up an efficient landing sequence and conflict free, simulation models could help to analyze the operational efficiency of the current ATC procedure together with airport operations and propose new procedures to optimize the use of available airspace in terms of capacity, environmental aspects, and where possible in terms of track by a proper integration of flows in busy traffic periods [4].

The ATLANTIDA project is a research effort in the air traffic management domain leaded by BR&TE together with key research companies and Spanish universities, with the aim of providing a significant contribution to the attainment of the common European goals set by the SESAR program and beyond. Universitat Autònoma de Barcelona (UAB) has been collaborating with Boeing Research & Technology Europe, ATOS-Origin and INDRA in the development of a causal model to improve CD/CR algorithms performance

The conflict resolution consists in avoidance maneuvers applied by the concerned aircraft. These maneuvers can be heading angle changes (i.e. horizontal deviation), velocity changes, or vertical maneuvers, such as flight level changes for stable aircraft. In a landing sequence, each aircraft concerned computes a conflict-free trajectory for itself An aircraft is considered in conflict if there exists an instant when the vertical separation and the horizontal separation minima is lost [12].

A simulation model that could cope with the TMA airspace capacity should integrate and manage different sources of information to analyze the perturbations that affect the different arrival flows and design mitigation mechanism to avoid the propagation of those perturbations on the runway throughput. Thus, the model should consider data such as:

- Number of aircrafts in the TMA arrival flows.
- Expected trajectories profile: waypoint pass time, speed, weight.
- Maintaining expected minimum separation standard (MSS);
- Current state of aircraft (level flight; altitude; speed; passing time);
- Geometry information: merging points, entry points, CDA profile for the different aircrafts.

This paper proposes a discrete event model in Coloured Petri Nets (CPNs) for merging arrival flows in an optimal and conflict free sequence of landing aircraft that deals with similar ideas as the Point Merge (Eurocontrol). One of the most important similarities between both approaches is the use of a pre-defined route structure: Terminal Control Area (or Terminal Manoeuvring Area) (TMA) trajectories are characterized by one IAF and a sequence of waypoints some of which are used as merging points with other arrival trajectories. In order to preserve safety distances at merging points speed adjustments must be properly evaluated which are implemented by means of a path stretching/shortening technique. Thus, CPN model compute the exact turning points, (see Fig. 1) according to the type of aircraft (heavy/medium/light), the entry time at the IAF, the expected speed and the safety distance that should be preserved at the merging point.

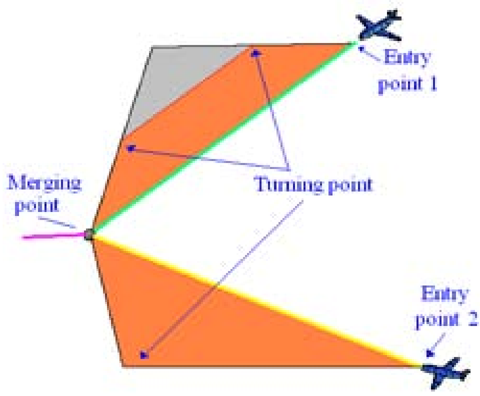

Figure 7-1: Example of new trajectory with turning point.

In section II the problem scenario is presented and an overview of the conflict detection and resolution algorithm proposed is explained. Section III summarizes the main aspects behind Coloured Petri Nets (CPNs) algorithm. Section IV provides the model description proposed and finally a summary and conclusions are presented in section V.

7.2 Problem Scenario

In the proposed Air Traffic Management System architecture, each aircraft follows a nominal path from source airport to destination airport described by a sequence of waypoints which are fixed points in the airspace. Furthermore, each fixed point has attached a time stamp which represents the expected aircraft pass time through the waypoint (Four dimension trajectories, 4DT's). This pre-defined route structure will be call route. The proposed algorithms are based in a given a sequence of aircraft entering by three different IAFs, flying by its corresponding three routes and a single landing runway.. This routes must join into one route as shown in Fig. 2, by merging in two different merging points.

In the present model, the Gran Canaria TMA is used to test the CPN model (see Fig. 2). There are three different approaching routes from Europe (IAF *1-Rwy*, IAF *2-Rwy* and IAF *3-Rwy*); two different intersection waypoints called *Merging point 1(Fayta)* and *merging point 2(Cannis)*. If the approaching is done by IAF *2 (Rusik)* or *3* (Nwpt) then the *Merging point 1* is the first waypoint where these two routes fuse into one. If the approach is done by IAF *1(Terto)* then the merging point is *Merging point 2;* in here the three routes (two previously fused), fused again (see Fig. 2).

Conflict detection (CD) is addressed in the proposed model in the following way: The time stamp of the leading and the following aircraft are compared when passing into a merging point to verify if safety distance (sd) is preserved.

As soon as the aircraft arrives at its corresponding IAF, a certain control action is evaluated to guarantee that the aircraft will arrive at the merging point, exactly at a safety distance (in time)of its heading aircraft. The safety distance in the merging point is evaluated independently of the route of each aircraft but taking into account the characteristics of each aircraft (weight). It is important to note that the new expected arrival time is computed at the arrival of the aircraft at the TMA, thus, control actions can be taken at the TMA entry point for each particular aircraft according to the delay to be generated or absorbed.

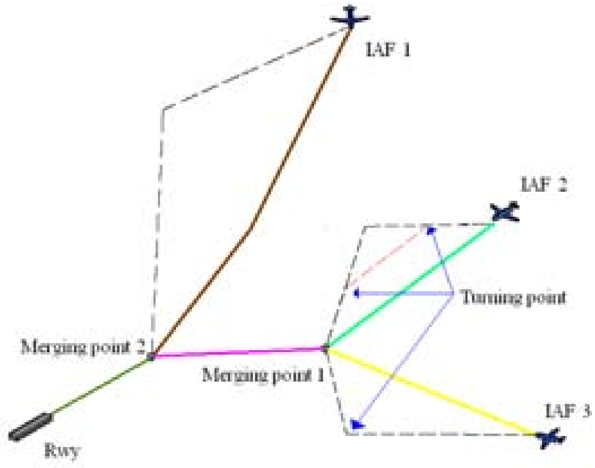

Figure 7-2: Three trajectories with two merging points.

The predictive model computes and detect Medium Term Conflicts each time there is a new TMA arrival at any entry point, just by evaluating the passing time at the merging points and checking if the time between two consecutive aircrafts is smaller than the minimum separation standard (MSS) given in Table I.

Table 7-1: Minimum Separation Standards (MSS). MINIMUM TIME BETWEEN SUCCESSIVE ARRIVALS AND DEPARTURES

Leading aircraft	**Following aircraft**					
	Heavy		**Medium**		**Light**	
Heavy	**96**	**60**	**120**	**90**	**144**	**120**
Medium	**72**	**60**	**72**	**60**	**96**	**90**
Light	**72**	**60**	**72**	**60**	**72**	**60**

Control actions that are implemented into the DES model to avoid a conflict (called conflict resolution: CR) are divided in three general aspects.

- Evaluate an alternative trajectory (also called change of vector).
- To speed up the aircraft.
- To decrease the speed of the aircraft.

All control actions are performed by the following aircraft in a look ahead perspective and all are explained bellow. Fig. 3 summarizes the different control mitigation actions implemented as events that can be fired according to time stamp information in the merging points.

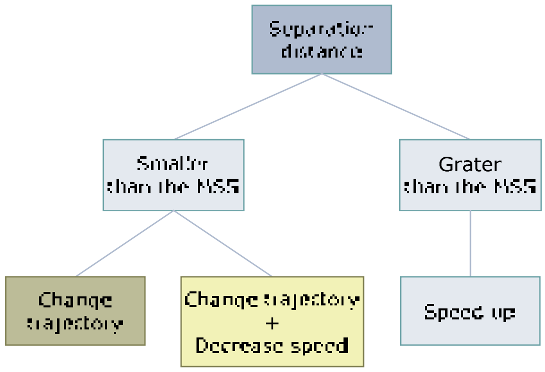

Figure 7-3: Control actions.

7.2.1 PATH SHORTENING/PATH STRETCHING CONTROL ACTION

The objective of the change of vector is to stretch distance to be flown from the TMA to the merging point so an aircraft can arrive at the expected time maintaining its speed profile. Therefore, the delay required is absorbed by the alternative trajectory proposed.

In these algorithms the first approach to solve conflicts starts by modifying the trajectory to be flown. If the difference between the passing time of the leading and the following aircraft is less than the MSS (a conflict is detected) then the following aircraft change its original to modify the passing time to a later time so conflict is avoided.

The delay (in time) needed to arrive on time at the merging point is calculated by comparing desired arrival time at the merging point minus the expected arrival time at the same merging point. This delay obtained is used to calculate the new distance to be flown (see Fig. 4).

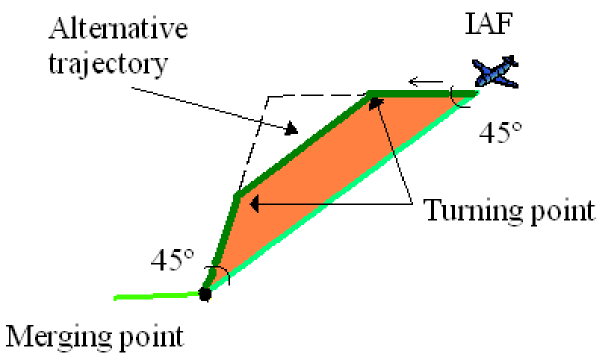

Figure 7-4: Alternatives trajectories.

To generate the alternative trajectory the new distance to be flown is applied straightforward to a predefined conflict resolution route as shown in Fig. 4. Thus, according to the delay that should be applied to satisfy the desired arrival time at the merging point, and preserving at the same time the speed profile, the aircraft turns 45º until a certain turning point in which the aircraft is redirected (could be parallel to the original route) towards the merging point. The geometry of the alternative trajectory can be triangle or trapezium shaped (see Fig.4).

7.2.2 SPEED UP CONTROL ACTION

The objective of the speed up of the following aircraft is to reduce time to be flown from the TMA entry point to the merging point so and aircraft can avoid runway idleness or future conflicts but ensure a safety distance based on the MSS. By considering that distances between IAFs and the merging points are known variables, the nominal speed profile can be computed straightforward just using the desired time arrival at the merging point.

The following aircraft is speed up until the MSS (according to Table I) is reached or as close to this one as possible (called best separations distance). Then, the best separation distance is the minimum possible distance between the leading and the following aircraft that depends on medium speed (not exceeding a maximum or minimum speed of each aircraft) and the initial time in the TMA that guarantees there is no conflict between them.

7.2.3 DECREASE SPEED CONTROL ACTION

The objective of decreasing speed of the following aircraft is to augment time to be flown from the TMA to the merging point. This alternative will be used only when the delay obtained through the stretching technique cannot solve the conflict detected at the merging point, and an extra delay is required.

7.3 Coloured Petri Net optimization approach

Coloured Petri Nets (CPN) have proved to be successful tools for modelling complex systems due to several advantages such as the conciseness of embodying both the static structure and the dynamics, the availability of the mathematical analysis techniques, and its graphical nature.

The main CPN components that fulfill the modelling requirements are:

- Places: They are very useful to specify both queues and logical conditions. Graphically represented by circles.

- Transitions: They represent the events of the system. Graphically represented by rectangles.

- Input Arc Expressions and Guards: Are used to indicate which type of tokens can be used to fire a transition.

- Output Arc Expressions: Are used to indicate the system state change that appears as a result of firing a transition.

- Colour Sets: Determines the types, operations and functions that can be used by the elements of the CPN model. Token colours can be seen as entity attributes of commercial simulation software packages

- State Vector: The smallest information needed to predict the events that can appear. The state vector represents the number of tokens in each place, and the colours of each token.

The Colour sets will allow the modeller to specify the entity attributes. The output arc expressions will allow specifying which actions should be coded in the event routines associated with each event (transition). The input arc expressions will allow specifying the event pre-conditions. The state vector will allow the modeller to understand why an event can appears, and consequently to introduce new pre-conditions (or remove them) in the model, or change some variable or attribute values in the event routines to disable active events.

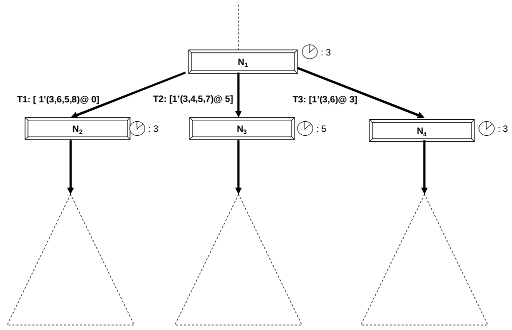

Figure 7-5: First 2 levels of a coverability tree.

From the OR point of view, the CPN model can provide with the following mathematical structures:

- Variables: A variable can be identified for each colour specified in every place node.
- Domains: The domains of the variables can be easily determined by enumerating all the tokens specified in the initial state.
- Constraints: Can be obtained by straightforward from the arc and guard expressions. Arc expressions can contain constant values, colour variables or mathematical expressions.
- From the AI point of view, the coverability tree of a CPN model allows to determine:
- All the events that could appear according to a particular system state (Fig. 5).
- All the events that can set off the firing of a particular event.
- All the system states (markings) that can be reached starting from a certain initial system operating conditions M0.
- The transition sequence to be fired to drive the system from a certain initial state to a desired end-state.

7.4 Model description

The medium term CD&CR model proposed has been specified in the Coloured Petri Net (CPN) formalism. The discrete event approach has been specified using seven colours, five places and nine transitions. This model can be integrated with the AMAN/DMAN CPN model [6] to optimize a shared mode runway in which the best landing sequence can also be computed.

As shown in Fig. 3, three different control actions attached to each merging point could be fired. These events are represented by different transitions in the CPN model.

- The event “Change trajectory” takes place when a conflict between two aircraft is detected in a merging point. Taking into account the scenario presented in Fig. 2, three transitions derivates from this event: Change trajectory from IAF 1 to merging point 2, change trajectory from IAF 2 to merging point 2 and finally change trajectory from IAF 3 to merging point 2.

- The event “Change trajectory + decrease speed” takes place when a conflict between two aircraft is detected in a merging point and can not be solved only by a changing vector procedure. Therefore, taking into account the scenario presented in Fig.2, three transitions derivates from this event: reduce speed from IAF 1 to merging point 2, reduce speed from IAF 2 to merging point 2 and finally reduce speed from IAF 3 to merging point 2.

- The event “Speed up” takes place when the separation distance between the leading and the following aircraft is greater than the MSS. In order to acquire a reduction of time from the TMA entry point to the merging point the following aircraft is accelerated until an optimal or best separations distance (in time) is reached. Another transition is used to compute the speed profile along the new trajectory so no extra speed changes will be required.

7.4.1 NET SPECIFICATION & DESCRIPTION

Table II summarizes the colours used to describe all the information required in the places to define the aircraft trajectory in 4D.

Place specifications are shown in Table III and detailed as follows: In the CPN representation, “*Segments*” place node has information regarding each aircraft trajectory sucha as: Colour *aid* corresponds to the aircraft identification in a trajectory; the first *idp* colour corresponds to the waypoint identification of the beginning of the trajectory (entry point in the TMA) while the second *idp* keeps the information regarding to the passing waypoint identification; colour *t* and *vel* carry on its corresponding current time and speed. The third *idp* colour corresponds to the next waypoint identification of the trajectory while second colour *t* has information about IAFs entry time. Finally the *t* and *de* colour corresponds to IAFs entry time and distance in the TMA, respectively.

Table 7-2: Colour specification

Colour	Meaning
aid	**Aircraft identification**
idp	**Waypoint identification**
t	**Time**
vel	**Average speed**
de	**Distance between two waypoints**
c	**Control variables**
wp	**Waypoint information**

Table 7-3: Place specification

Place	Colour	Definition
Segments	**S**	**aid*wp*wp*t*v*wp*t*de**
G	**G**	**c,c,c**
Solution	**R**	**aid,wp,v,de**
Pair	**P**	**aid, aid,t,wp,wp**

Place "*G*" considers only three colours as shown in Table III. The first colour (ie. *d10) takes a value 0* only when the pair of consecutive aircrafts has not previously evaluated or they have been forced to change the speed in order to avoid conflicts. The same colour takes value *2* when the pair of aircrafts has to be evaluated in merging point 1 after a vector change (path stretching) has been proposed. Finally, colour *d10 takes value 3* when the pair of aircrafts has to be evaluated in merging point 2 after a speed-up control action has been applied. Colour *c3* and *c4* are control variables that indicate the number of the following aircraft to be evaluated in Fayta and Canis, respectively. Therefore if the transition concerns to Fayta, colour *c3* will be incremented in one unit to update the next pair to be evaluated in this waypoint.

Place "*Solutions*" store the information regarding to the aircraft successfully solved. This node contains the aircraft identification, its corresponding passing time, medium speed and distance to be flown.

Place "*Pair*" contains the information that links the leading and the following aircraft ('*x1*' and 'y1', respectively) with the next passing time (*x11*) of aircraft '*y*' and a control variable (*c3* or *c4*) that indicates the following aircraft to be evaluated in Fayta or Canis. After firing this transition the information is properly updated in all place nodes since the vector change has been completed.

7.5 Event specification example

Fig. 6 illustrates an event (represents an aircraft that will be speed up) that formalize the CD&CR model for merging point 1.

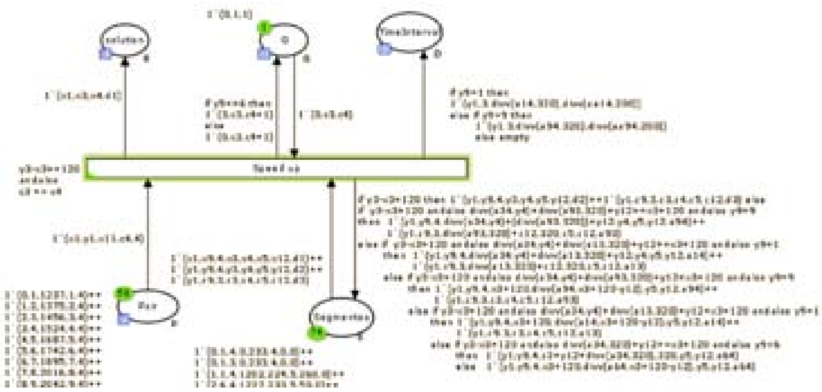

Figure 7-6: Example of the CPN for the CD&CR algorithm.

The CPN shows five nodes; the node "*Segments*" asks as initial conditions for a pair of aircraft (*x1* & *y1*) that comes from their corresponding passing waypoint identification (*x9, y9 & z9*) and they are evaluated when passing in merging point 1 (*x2=y2=4*) and with passing time, speed profile, next waypoint identification, IAFs entry time and distance from IAFs (*x3,x4,x5,x12,d1* & *y3,y4,y5,y12,d2* & *z3,z4,z5,z12,d3* respectively).

As initial conditions, node "*Pair*" asks for the same pair of aircraft that node "Segments" (*x1* & *y1*), with a next passing time (*x11*), *c4* as a control variable to indicate the following aircraft, and finally *c3=4* indicating they are evaluated when passing in merging point 1).

Information supported in node "*G*" is used when colour *d10 takes value 0 since* the following aircraft has not been previously evaluated, and *c3,c4* are linked to node "*pair*".

When all initial conditions are properly specified in each place node, then node "*Solutions*" stores only information regarding the leading aircraft (note that this aircraft will not have conflict with any other aircraft). Node "*G*" will increase colour value *c4* in one unit to specify that the next aircraft has changed and should be evaluated; and if the following aircraft comes from IAF 2 or 3, *d10=3* in order to be re-evaluated in merging point to solve any possible conflict in this passing waypoint.

Finally place "Segments" will return information about the following aircraft with its corresponding new passing time in merging point 1, new speed profile , and/or new distance to be flown, if required.

7.6 Case Study

Arriving flow to the Gran Canaria TMA landing at Gran Canaria airport at a busy traffic period use to be between 20 to 30 aircraft in one hour. To test the performance of the proposed CD/CR CPN model, a synthetic traffic workload of 35 arrival aircrafts has been designed. The arrival traffic sequence is assumed to have been determined upstream in the extended TMA by an arrival manager (AMAN). Therefore sequencing is implicitly defined in the traffic preparation input file.

Aircraft arrivals through the same entry point are conflict-free between them; however the merging of these arrivals generate conflicts at the merging point areas.

Table IV illustrates the 4DT specification of the first three aircraft arriving to Gran Canaria TMA. As it can be noted, 2 aircraft arrive through Rusik entry point and one aircraft arrives through Terto entry point. The aircrafts arriving through Rusik are conflict free between them, but there is a conflict in Cannis merging point.

Table 7-4: Two trajectories example

No	TMA entry time (s)	TMA IAF	WPT merging point 1	WPT time (s)	WPT TAS (m/s)	WPT merging point 1	WPT time (s)
1	260	2	3	972	224	4	1202
2	50	1	3	---	233	4	1237
3	470	2	3	1154	233	4	1375

According to this information in Table IV, the initial marking for places has the format shown in Table V.

Table 7-5: Initial marking for two trajectories example

Place	Initial marking
Segments	1`(1,1,3,972,224,260,0)+1`(1,1,4,1202,224,260,0)+ 1`(2,6,3,0,233,50,0)++1`(2,6,4,1237,233,50,0)++ 1`(3,1,4,1375,233,5,470,0)+ 1`(3,1,3,1154,233,4,470,0)
Pairs	1`(0,1,1237,1,4)++1`(1,2,1375,2,4)++1`(2,3,1456,3,4)
G	1`(0,1,1)
Solution	empty

For these three trajectories a feasible conflict free solution is reached (Table VI). It can be noticed that the aircraft number 1 has been accelerated (to 290m/s) and has new waypoint passing time in merging point 1 of 810s instead of 972s and in merging point 2 the passing time has changed from 1202s to 988s, as a result aircraft 3 has also a new waypoint passing time of 1043 instead of 1154 in merging point 1, and its corresponding speed has also been changed to 278m/s.

Table 7-6: Solution for two trajectories example

No	TMA entry time (s)	TMA IAF	WPT merging point 1	WPT time (s)	WPT TAS (m/s)	WPT merging point 1	WPT time (s)
1	260	2	3	810	290	4	988
2	50	1	3	---	290	4	1108
3	470	2	3	1043	278	4	1228

The entirely model has been tested with 35 aircraft and the results are shown in Table VII (see the Appendix A). Information about aircraft are black colored while the results are in red color to be identified easily.

At the right hand side of figure 1, a trombone area representing the PM approach with two entry points is represented, while at the left hand side of the same figure the fixed re-routes of the new approach are also represented for the same TMA configuration. Thus, with the proposed method, each entry point has associated a fixed re-route which is computed by a turn of 45º from the arrival route at the IAF.

One of the main differences between both methodologies is the geometrical configuration of the model proposed. Figure 1 shows a difference in terms of the use of path shortening or path stretching technique.

Furthermore, the proposed model has been tested using three different IAFs and two merging points, providing excellent results for a traffic peak. In fact the causal CPN model could be extended to different number of IAF and merging point configurations, while multiple point merge systems require the analysis of particular solutions to evaluate the cause effect configuration.

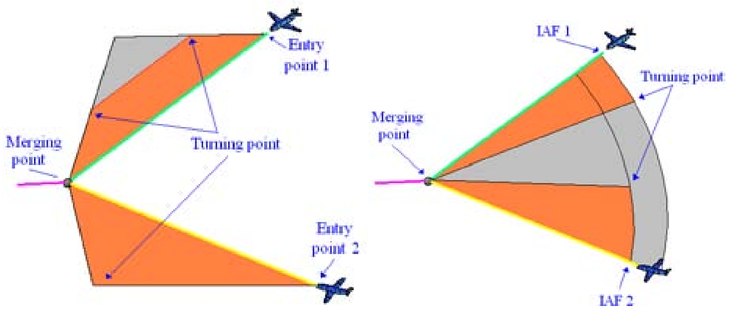

Figure 7-7: Example of new trajectory with turning point.

7.7 Conclusions

The proposed approach has modelled the CD&CR problem for multi-aircraft using a discrete event approach in the CPN formalism. A case study with 35 arrival aircrafts has been successfully solved.

The CD&CR model computes the future passing times, speed and positions of each aircraft according to certain characteristics (heavy, medium, light). The safety distance requirements due to vortex turbulences at merging points are specified to solve the problem properly. The solution is obtained using the reachability tree in CPN. A computer simulation has used to generate a feasible 4DT solution. The model scope can be extended with consume fuel aspects (BADA referenced) in order to design a cost function that would allow an efficient exploration of the reacheability tree.

One of the key-point of such a design is the use of the state space to understand the behavior of the model. Furthermore, the model has been designed in order to help the modeller to design new procedures to solve problems regarding the future free flight concept.

7.8 Acknowledgment

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commercial airport" CICYT Spanish program TRA2008-05266/TAIR, and the ATLANTIDA project: "New technologies applied to UAV's for research and ATM development" (CEN20072008)

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7.10 Apendix A

In this section the case study information can be found. Case study has been with 35 aircraft with initially 10 conflicts detected in the first point merge and 21 more conflicts in the second point merge. The results as well as all the regarding information to the name and nominal passing time of the IAF, nominal speed, distance to be flown, new speed and passing time, are shown in Table VII.

TABLE VII. 35 TRAJETORY STUDY CASE

	TMA entry time	TMA IAF	WPT TAS (m/s)	WPT name	WPT TAS (m/s)	WPT name	WPT nominal time (s)	WPT TAS (m/s)	New WPT time (s)	New speed (m/s)	Distances to be flown (m)	WPT name	WPT nominal time (s)	WPT nominal TAS (m/s)	New WPT time (s)	New speed (m/s)	Distances to be flown (m)	WPT nominal time (s)	WPT nominal TAS (m/s)
1	260	RUSIK	224	FTV	224	FAYTA	971,93	224	810	290	159867	CANIS	1202	218,67	988	290	211350	1373,23	191,19
2	50	TERTO	233	LZR	233	BETAN	978,90	233		290		CANIS	1237	221,20	1108	283	300208	1404,94	196,05
3	470	RUSIK	233	FTV	233	FAYTA	1154,47	233	1043	278	159867	CANIS	1375	224,06	1228	278	211350	1541,98	197,55
4	870	NWPT				FAYTA	1224,84	224	1050	274	79651	CANIS	1456	213,84	1348	274	131134	1630,42	188,52
5	180	TERTO	224	LZR	224	BETAN	1250,18	224				CANIS	1524	203,47	1468	233	300208	1706,55	181,41
6	400	TERTO	233	LZR	233	BETAN	1328,90	233				CANIS	1687	221,20	1588	252	300208	1754,94	196,05
7	800	RUSIK	224	FTV	224	FAYTA	1511,93	224	1486	232	159867	CANIS	1742	218,67	1708	232	211350	1913,23	218,67
8	990	RUSIK	233	FTV	233	FAYTA	1674,47	233	1623	252	159867	CANIS	1895	224,06	1828	252	211350	2061,98	197,55
9	1430	NWPT				FAYTA	1784,84	224	1625	253	79651	CANIS	2016	213,84	1948	253	131134	2190,42	188,52
10	1100	RUSIK	224	FTV	224	FAYTA	1811,93	224	1812	224	159867	CANIS	2042	218,67	2068	224	216832	2213,23	218,67
11	1290	RUSIK	233	FTV	233	FAYTA	1974,47	233	1969	235	159867	CANIS	2195	224,06	2188	235	211350	2361,98	197,55
12	1000	TERTO	233	LZR	233	BETAN	1928,90	233				CANIS	2287	221,20	2308	233	304764	2354,94	196,05
13	1800	NWPT				FAYTA	2154,84	224	2155	224	79651	CANIS	2386	213,84	2428	224	140672	2560,42	188,52
14	1180	TERTO	224	LZR	224	BETAN	2250,18	224				CANIS	2524	203,47	2548	224	306432	2706,55	181,41
15	1700	RUSIK	233	FTV	233	FAYTA	2384,47	233	2295	233	138635	CANIS	2605	224,06	2668	233	225544	2771,98	197,55
16	2060	NWPT				FAYTA	2414,84	224	2415	224	82979	CANIS	2646	213,84	2788	224	163072	2820,42	188,52
17	1500	TERTO	233	LZR	233	BETAN	2428,90	233				CANIS	2787	221,20	2908	233	328064	2854,94	196,05
18	1905	RUSIK	224	FTV	224	FAYTA	2616,93	224	2670	224	171459	CANIS	2847	218,67	3028	224	251552	3018,23	218,67
19	1690	TERTO	224	LZR	224	BETAN	2760,18	224				CANIS	3034	203,47	3148	224	326592	3216,55	181,41
20	2200	RUSIK	233	FTV	233	FAYTA	2884,47	233	2924	233	168751	CANIS	3105	224,06	3268	233	248844	3271,98	197,55
21	1900	TERTO	233	LZR	233	BETAN	2828,90	233				CANIS	3187	221,20	3388	233	346704	3254,94	196,05
22	2420	RUSIK	224	FTV	224	FAYTA	3131,93	224	3095	224	151200	CANIS	3362	218,67	3508	224	243712	3533,23	218,67
23	2860	NWPT				FAYTA	3214,84	224	3215	224	91939	CANIS	3446	213,84	3628	224	172032	3620,42	188,52
24	2150	TERTO	224	LZR	224	BETAN	3220,18	224				CANIS	3494	203,47	3748	224	357952	3676,55	181,41
25	2650	RUSIK	224	FTV	224	FAYTA	3361,93	224	3464	224	182336	CANIS	3592	218,67	3868	224	272832	3763,23	218,67
26	2400	TERTO	224	LZR	224	BETAN	3470,18	224				CANIS	3744	203,47	3988	224	355712	3926,55	181,41
27	2900	RUSIK	233	FTV	233	FAYTA	3584,47	233	3685	223	182905	CANIS	3805	224,06	4108	233	281464	3971,98	197,55
28	2600	TERTO	233	LZR	233	BETAN	3528,90	233				CANIS	3887	221,20	4228	233	379324	3954,94	196,05
29	3450	NWPT				FAYTA	3804,84	224	3805	224	121059	CANIS	4036	213,84	4348	224	201152	4210,42	188,52
30	2820	TERTO	224	LZR	224	BETAN	3890,18	224				CANIS	4164	203,47	4468	224	369152	4346,55	181,41
31	3300	RUSIK	224	FTV	224	FAYTA	4011,93	224	3892	224	132608	CANIS	4242	218,67	4588	224	288512	4413,23	218,67
32	3750	NWPT				FAYTA	4104,84	224	4334	212	123915	CANIS	4336	213,84	4708	212	204008	4510,42	188,52
33	3100	TERTO	233	LZR	233	BETAN	4028,90	233				CANIS	4387	221,20	4828	233	402624	4454,94	196,05
34	3600	RUSIK	233	FTV	233	FAYTA	4284,47	233	4604	233	233991	CANIS	4505	224,06	4948	233	314084	4671,98	197,55
35	3300	TERTO	224	LZR	224	BETAN	4370,18	224				CANIS	4644	203,47	5068	224	396032	4826,55	181,41