# Colored Petri Net Based Formal Airport Control Model for Simulation and Analysis of Airport Control Processes

Bernd Werther, Christoph Moehlenbrink, and Michael Rudolph

German Aerospace Center, Institute of Flight Guidance, Lilienthalplatz 7,
38108 Braunschweig, Germany
{Bernd.Werther,Christoph.Moehlenbrink,Michael.Rudolph}@dlr.de

**Abstract.** The development of the experimental Remote Tower Operation Human Machine Interface and the new Remote-Controller work position is supported by a cognitive work and task analysis (CWA) of the presently existing work environment and decision processes at airport Leipzig. This paper presents a formal approach for the description of the whole Human Machine System. It is shown how the results of a cognitive work analysis on a medium size airport are transferred into a formal executable human machine model for simulating the controllers work processes in relation to the airport processes. The model is implemented with Colored Petri Nets. The mathematical basis of Petri Nets allows a formal analysis of whole systems. Critical system states and inconsistencies in the human machine system are identified through comparison of knowledge states of the controllers with process states of the airport system by using State Space analysis. The represented formal work process model provides a valuable support for the communication between domain experts and system developers.

**Keywords:** Airport control model, Human Machine System, Colored Petri Net, State Space, Cognitive work analysis.

## 1 Introduction

Remote Tower Operation (RTO) describes the goal of remote control of small airports and of movement areas of large airports which are not directly visible from the tower. This is achieved by means of an augmented vision video panorama. In 2005 the DLR project RapTOr [1] was initiated in order to realize an RTO experimental system as extension of the Advanced Surface Movement Guidance and Control System (A-SMGCS) at the Braunschweig research airport.

Analysis and simulation of the tower work procedures as introduced in this paper support the design and development of the future tower work positions. The design process for a RTO work environment relies on interviews from domain experts (controllers) of the German Air Traffic Control Organization (DFS), in particular with respect to the work analysis and the validation of the work process model [2]. Initial design goal of RapTOr (Remote airport Tower Operation research) is the integration of the RTO work position into an existing tower work environment of a medium size airport in order to simultaneously control one or more neighboring small airports. The

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project encompasses as a major research and development goal, the simulation of operator decision making within the Tower work positions. The starting point of the model based design process is a formal description of current tower and ground control processes in a generic Petri net model. With the homogeneous description of the human machine system based on Colored Petri Nets it is possible to investigate the consistency of the human and the process model based on formal analysis as suggested in [3].

In section 2 the methodical approach and initial results of a tower work and task analysis is described, following a systematic procedure developed by Vicente [4]. The development of a formal Colored Petri Net model for description of controllers work processes is introduced in section 3, realized with CPN-Tools [5, 6]. The model serves for simulating the operator's decision making processes with the work analysis data as input. Section 4 presents first steps in validation of the work process model. Section 5 provides a conclusion and outlook with regard to the design process of future RTO work position.

## 2 Methodical Approach

The design and development of the experimental RTO HMI is supported by a cognitive work and task analysis (CWA) of the presently existing work environment and decision processes on airport Leipzig. The formalized results serve as input data for a human machine model for the simulation of the controller decision making processes at the tower work positions. This section introduces the work analysis method and the work process model approach.

The CWA is based on a formal procedure suggested by Vicente [4], separating the analysis into five phases: (1) work domain analysis, (2) control task analysis, (3) strategy analysis, (4) analysis of social organization and cooperation, (5) operator competency analysis (the latter however not being considered in this phase of the RapTOr project). Details of the CWA as well as the cognitive modeling and simulation using Colored Petri Nets are described in [4, 7 and 8].

The work domain analysis aims at analyzing the aircraft movements. For this purpose the air-to-air process which describes the complete movements from arrival to departure is treated separately for the different control areas (e.g. approach, runway, taxi and apron). Acquired information and possible actions are attributed to corresponding control areas. Accessible information from the different sources (e.g. visual view from the tower windows, approach radar) and possible actions via the corresponding interaction devices (e.g. radio, telephone) is acquired without considering the controllers tasks in this first phase. In the control task analysis phase the tasks are identified which have to be completed. Here decision and support processes are treated separately. The task description follows a well defined structure which covers the triggering event, the preconditions, the task containing coordination, and the post-condition. The strategy analysis is the most laborious phase. This is because controllers to a large extent use implicit knowledge which is hard to extract. In an empirical study [9] Sperandio e.g. detected strategy differences, dependent on workload. The development of strategies depends extensively on the handling of goals under restricted cognitive resources [10]. This is one important motivation for the resource based Petri net modeling technique. An important aspect of multiple task situations as typical for controllers is the relative weighting of different simultaneous goals with respect to each other. Action strategies evolve due to limited human processing capacity [8]. Phase 5, the analysis of cooperation and social organization yields a clear tasks and functions allocation for the two controllers (ground controller (PG), tower controller (PL)) within the current air traffic control procedures. The future RTO workplace, however, represents a significant change of this situation. On the one hand the augmented vision video panorama offers revolutionary new possibilities for the support of air traffic controllers. On the other hand the integration of remotely located control areas within the present day tower environment represents a completely new work condition.

## 3 Formalization of Cognitive Work Analysis Results with Colored Petri Nets

In this section the different levels of the Petri net architecture resulting from the work analysis process will be introduced in detail. To graphically indicate the hierarchical structure and different levels of the model, transition framed sub networks are replaced by transitions with light grey boxes (see Fig.1) on next higher hierarchy level. Places which are connected with a higher hierarchical level are marked with grey boxes on the lower network level (Fig.2).

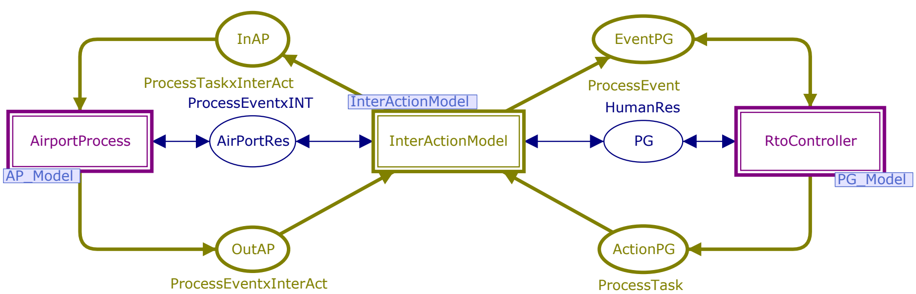


**Fig. 1.** Controlled airport system as Human Machine System is mapped on the highest hierarchy level of a Colored Petri Net. Transitions (rectangles) with grey boxes include subnets.

### 3.1 Cooperation Between Process Model and Controller Model

The results of the fourth CWA phase (cooperation) are fed into the highest hierarchical level of the CPN structure. Here the distribution of roles and functions among the different human operators and their technical support systems is defined. On this level the work process is described in a holistic manner whereas on the lower levels focus is put on the single work positions. Following an approach of Cacciabue

[11] a human machine model can be separated into three different Model types: Human Model, Interaction Model and Machine Model. An Interaction Model manages the connection between Human Model(s) and Machine Model(s). So Human Model(s) and Machine Model(s) can work independently from each other for some time periods. Fig.1 shows the realization of the airport control process with a focus on RTO controller work positions. The transition framed subnet *RtoController* describes the cognitive behavior of the RTO controller. The Interaction Model (*InterActionModel* as replacement transition, Fig.1) defines the controller interactions and includes networks for description of information resources, such as radio and far view.

The airport process model (*AirportProcess*, in Fig.1) describes the movement process of aircrafts. The state of the process model determines the type and content of information which can be acquired by the controller. This can be perceptible information about the status of airport resource usage (token on place *AirPortRes*) such as usage of taxiways or the occurrence of a specific event like aircraft is started up. Other possible information would be a request of a pilot via radio like *request start-up clearance*.

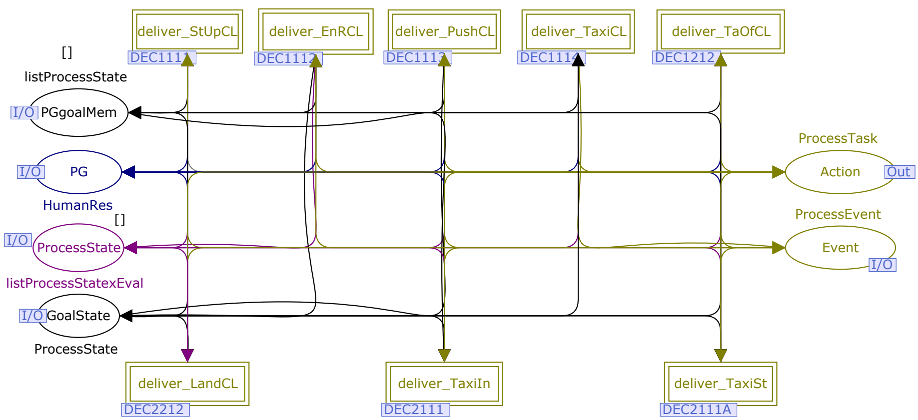


**Fig. 2.** In the mental model implemented tasks

## 3.2 Formal Description of Tasks

On the next lower level of the controller model (*RtoController* in Fig.1) within the Petri net architecture knowledge representation about the airport process (mental model) and the goal driven actions fulfilled by controllers are implemented. Control tasks are described explicitly and in great detail in operation instruction manuals of Air Traffic Control (ATC) organizations. There are also general rules for handling of more than one task or task object, such as the first come first serve rule. Depending on the situation the task coordination could be very different.

Fig.2 shows the tasks which are implemented in the model. In the current version of the FAirControl model the following tasks are implemented: Deliver (Start-up, Push back, En-route, Taxi (In), Taxi (Stand), Taxi (Out), Landing and Take Off) Clearance. This is the lowest set of tasks for description of the reduced inbound-outbound process on an airport. These transitions in Fig.2 labeled with light grey boxes represent those tasks and are sub nets on the next lower hierarchy level. The execution and processing of tasks are controlled by the active goals as tokens on the black place *GoalState* and knowledge about the current airport process state *ProcessState* on the purple place and the detected process events (place *Event* on the left side of Fig. 2).

The knowledge and information about the current work process (mental states) are represented by tokens. The results of the task processing would be situated on the place *Action* on the right side of Fig.2. The place *PG* considers the used human resource RTO controller which is responsible for these tasks. Different tasks in Fig.2 will be described on the next lower level by subnets. As an example the sub net within replacement transition *DEC1111* is shown in Fig.3.

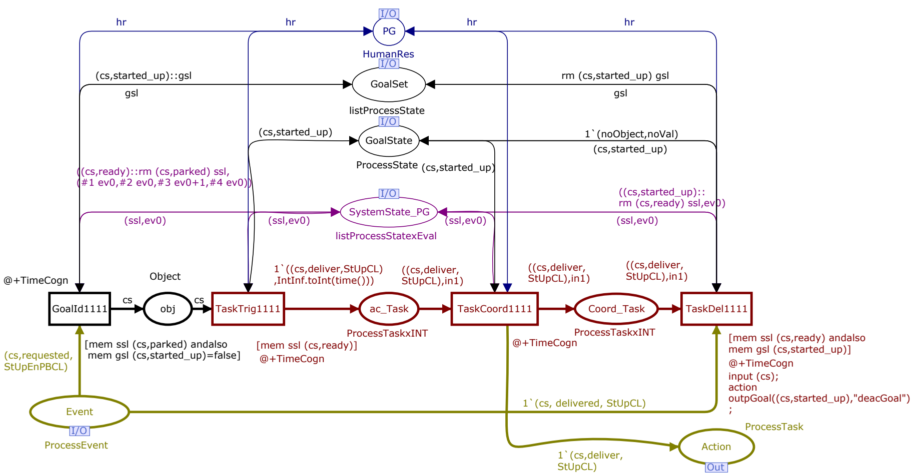


**Fig. 3.** Description of decision and support tasks, e.g. DEC1111 in Fig.2: task *deliver StartUp clearance*

The control tasks identified in CWA phase two are modeled with regard to the actions to be performed and the required and created information. As mentioned above control tasks are depicted in operation instruction manuals of Air Traffic Control (ATC) organizations. Generally decision and support tasks can be distinguished. Tasks are separated into those representing preconditions, others which coordinate the task (decision process, support process) and those actions which complete the task and lead to post conditions [12].

Fig.3 shows the net which is contained in transition *DEC1111* (Fig.2) for description of task *deliver start-up clearance*. By switching the transition *GoalId1111* the goal to deliver the start-up clearance will be added to the goal set. The task can be triggered if the transition *TaskTrig1111* fired by internal intended goal states, identified system states or when external events are detected in the airport process (cp. Fig.3). The Task from type *1`(LH120,deliver,StUpCL)* will be activated. This means that the Start-Up Clearance should be delivered to the pilot of an aircraft. If the transition *TaskCoord1111* fires all actions which are necessary for fulfilling the task are prepared. Through processing of these actions the modeled controller collects information about the work process und tries to find out if the conditions for executing the decision tasks are given. These actions are processed on next deeper level (action level) in the hierarchy. The lower hierarchy levels are not significant for this paper. More information is found in [12].

## 4 Identification of Controllers' Strategies Supported by Simulations

The work process structure introduced in this paper was developed together with domain experts in the CWA. During first validation steps based on defined scenarios the correctness of the logical process flow and ability of the controller models to separate the aircrafts was successfully tested in the model. In the following section the logic flow between work process model of the controllers and simulated airport process model are described. This is followed by the representation of simulations using more realistic traffic flows which should be controlled and guided. These generated scenarios are the basis for a model review and model refinement with domain experts. For a better communication with the domain experts the graphical visualization of the airport processes for a generic airport was realized, as shown in Fig. 4.

The next section starts with a short introduction of the FAirControl visualization, followed by the first results of an evolution of specific traffic scenarios.

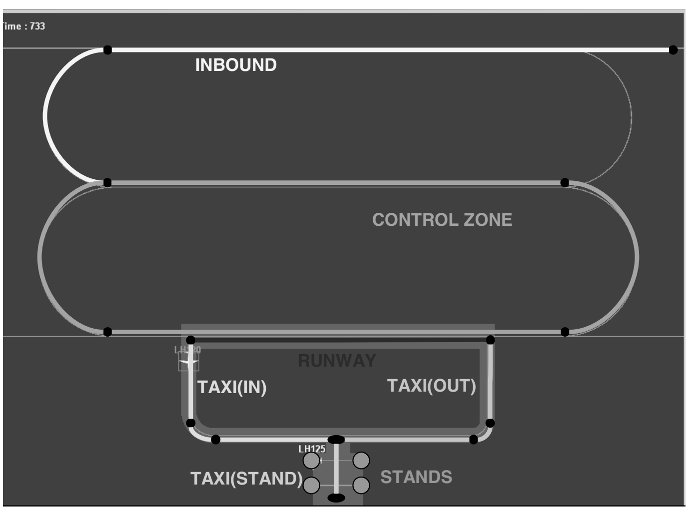


**Fig. 4.** Graphical visualization of the simulated controlled inbound/outbound sequence of a generic small airport with two controlled aircrafts

### 4.1 Visualization of Controlled Airport Processes

The executable model introduced in this paper should support the identification of controllers' strategies in organization of task and pursuance of goals. The traffic flow as represented in the airport process model has to move through different control areas which are inbound area, control zone, runway area, taxi fields and stand, each of those having a certain resource limitation. Fig.4 shows the control areas for a generic small Airport. An aircraft movement within the airport area is described by the following sequence: approach, landing, taxiing, going around, push-back, taxiing, take off and departure. The aircrafts (pilots) described in the process model need clearances from the controller to pass through the different control areas. So the controller model has to collect information about the airport resource usage via observation of the movement areas and also by messages and requests via radio (Fig. 5). These two channels are realized in the interaction model and enable the communication between airport process model and controller model.

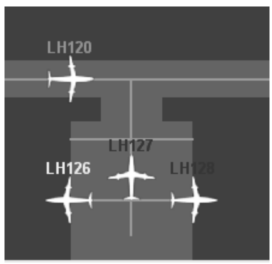


**Fig. 5.** Represents the graphical visualization of the pilot communication. The representation of label *LH127* (dark grey) shows, that the pilots send a request to the controller. The label *LH120* (grey) visualizes a message and *LH126* (light grey) represents no communication activity.

### 4.2 Evaluation of Specific Traffic Scenarios

After implementing the work analysis results into a Petri net the FAirControl visualization was used to discuss the correctness of the implementation with two domain experts. 14 static scenarios of the FAirControl airport, representing different possible global states of this microworld were presented to the controllers. Scenarios were discussed in respect to closeness to reality and task sequences. In order to find out about task sequences the experts anticipated the next four clearances that would be handled, assuming normal operation within each scenario. To give an example scenario 11 is shown in figure 6. First airplane LH125 will receive a take-off clearance, before LH132 will receive a taxi-in clearance. Then LH122 or LH124 will be cleared to be pushed before LH123 can land.

An insufficient understanding of information processing, memory, behavioral strategies and decision making for tower controllers is claimed in the literature [13]. Interviewing the tower controllers about action possibilities within each scenario is one first step to get an idea, how they interact with their environment. Going back to

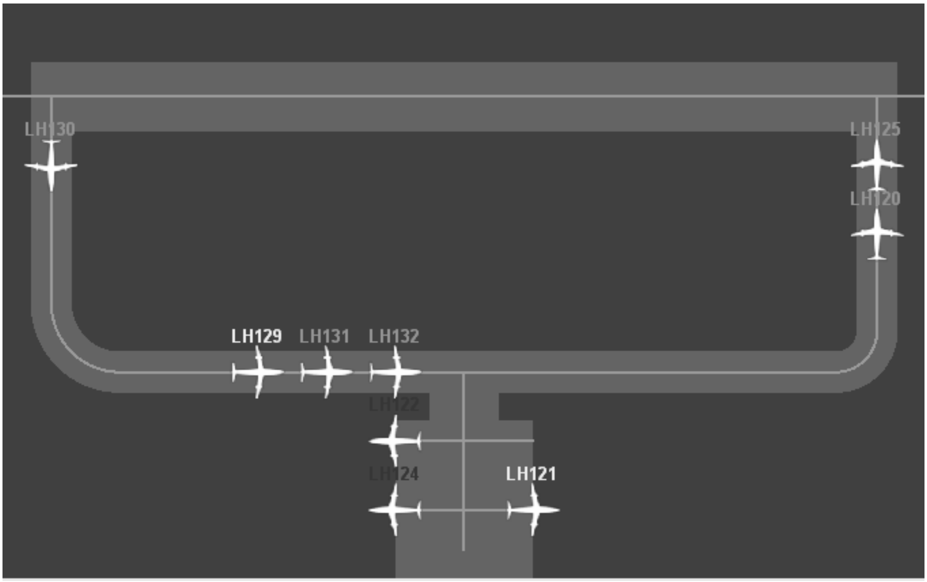


**Fig. 6.** A Cut-out of scenario 11: The airplane will be handled in the following order: 1) LH125 2) LH132 3) LH122/LH124 4) LH123 (not present in this cut-out)

the interviewer and discussing ones' understanding of the work analysis enables an iterative process in model development. Therefore we can conclude that a subject executing the FAirControl Model has several degrees of freedom to interact with the microworld comparable to a simplified tower control position.

The advantage of a Petri Net based mircoworld lies in the comparison of State Space results for each scenario with the subjects' behavior within the mircoworld. On the one hand the circumstances under which a controller gave a clearance can be reported. In addition, all action alternatives within the mircoworld can be depicted by the State Space. Figure seven represents part of the State Space for scenario 11, which was discussed with the controllers. A resource conflict is apparent on the apron area. LH132 asks for this resource to taxi-in, while LH122 and LH124 intend to use the same resource for push-back and taxi-out. Figure 7 enables an evaluation which clearance has to be given first, to get an optimal throughput in respect to time. To clear LH132 (taxi-in apron) first will result in a delay of 35 TS (timesteps) for LH124, but LH132 will reach the state "taxied-out" without delay (first case: $t_{LH124}$=110 TS, $t_{LH132}$=380 TS). Clearing LH124 (push-back, taxi-out) first is optimal for this airplane, but LH132 then will be delayed by 70 TS (second case: $t_{LH124}$=75 TS, $t_{LH132}$=310 TS).

Time critical decisions in respect to the most efficient throughput always occure, when the tower controller has to deal with resource conflicts. The formal State Space analysis offers an objective perspective to find out about optimal task sequences to handle the airport processes. For our example scenario 11 we can conclude, that the interviewed controllers suggested the best solution.

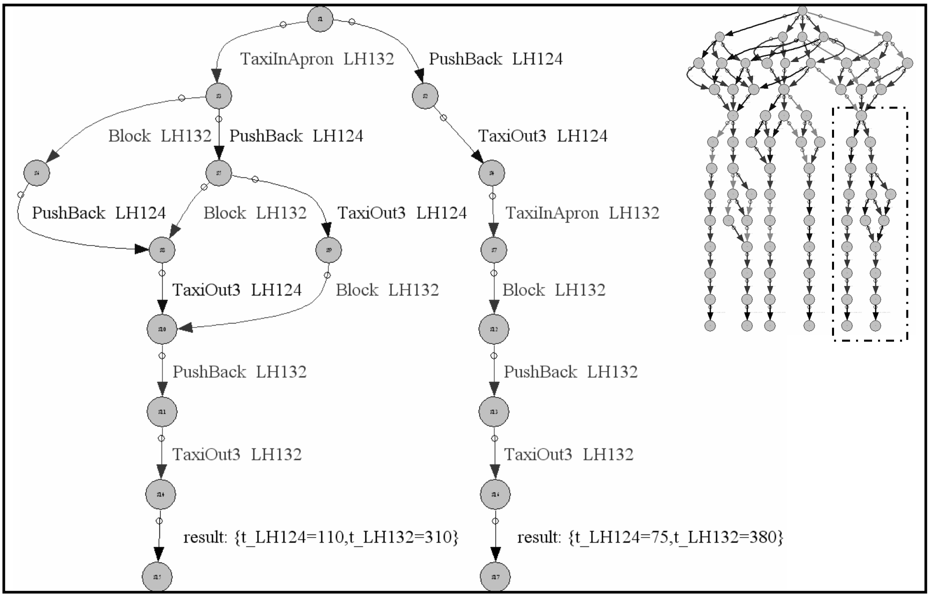


**Fig. 7.** The small State Space graph on the right side presents the possible traffic flow alternatives in scenario 11 (Fig. 6). The reduced State Space on the left side shows the conflict of two aircraft LH124, LH132 by usage of the same resource *Apron* as presented in scenario 11 more in the detail.

## 5 Conclusion and Outlook

The most important information source of each tower controller is currently the visual view out of the tower window. Under remote tower operations this critical information source will likely be replaced by an augmented video panorama. However, especially augmented tower vision (ATV) concepts, i.e. the superposition of additional information on the far view like weather data and aircraft labels with object tracking also raise questions regarding controllers attention and perception processes.

With the homogeneous description of the human machine system based on Colored Petri Nets it is possible to investigate the consistency of the controllers' strategies and actions and of the process model of airport movements. This is achieved by a formal analysis and comparison of the State Spaces of the internal mental representation of airport process in the mental model of the controllers on the one hand and simulated airport process in the identically named model on the other hand. Critical work situations can be detected and analyzed in an early phase of the system design and alternative solutions can be investigated by means of model based simulations.

The transfer of the CWA results into the formal controller models was introduced in this paper. The resulting model represents a basis for monitoring psychological parameters of the operators (e.g. work load), for deriving the operator requirements and for uncovering missing situational awareness by means of simulations and State

Space analysis in the future by using the method presented in [8]. Furthermore the graphically represented formal work process model provides a valuable support for the communication between domain experts and system developers.

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