Available online at www.sciencedirect.com

ScienceDirect

IFAC PapersOnline CONFERENCE PAPER ARCHIVE

IFAC PapersOnLine 52-11 (2019) 122–127

A socio-technical holistic agent based model to assess cockpit supporting tools performance variability

Miquel Angel Piera*. Juan Jose Ramos**
Jose Luis Muñoz***

- *Universitat Autònoma de Barcelona*

Spain (Tel: +34620625881; e-mail: miquelangel.piera@uab.cat).
*** Universitat Autònoma de Barcelona, Spain (e-mail: juanjose.ramos@uab.es)*
**** ASLOGIC sl.,*
Spain, (e-mail: jlmunoz@aslogic.es)}

Abstract: The mesh of information that influence a human actor in its decision-making process is difficult to formalize and more difficult to validate. Stochastic approaches to represent human performance provides a fast modelling approach that can be statistically validated, however, do not contribute to a better understanding of performance variability consequences neither the design of mitigation mechanisms in critical processes. Better modelling approaches are needed to support a deeper understanding of the causes of a poor performance and the propagation mechanisms that spark emergent behavior and its effects. In this paper it is presented an agent based modeling framework to identify those factors that affects the performance of the pilot flying cockpit functionalities considering different socio-technical operational conditions. As a result, it is expected the design of new cognitive computing supporting tools to improve pilot situational awareness.

© 2019, IFAC (International Federation of Automatic Control) Hosting by Elsevier Ltd. All rights reserved.

Keywords: Socio-Technical Systems, Influence Variables, Agent Based Modelling, Functional Resonance Analysis Method,.

1. INTRODUCTION

This Flight deck has experienced a huge technological evolution from early Clipper Model 314 with 5 crew positions (navigator, radio operators, flight engineer and 2 pilots) with a clear breakdown of operating responsibilities (aviate, navigate, communicate and manage system) to nowadays fly-by-wire and computer systems with 2 crew members in the cabin.

The introduction of new technologies in the cockpit has allowed important advances in communication, navigation and engine management technologies which have simplified and consolidated control mechanism with a direct reduction of workload for a variety of tasks and an indirect increment of allocated responsibilities to pilots which impact again with an increment of pilot workload.

A driver for the constant evolution of cockpit operations has been how to obtain the most of pilot performance from the least amount of displayed information required to support each flight task. Unfortunately, despite the well-recognized advantages of the introduction of automatism in cockpit operations, some problems have arisen: flight crews are not adequately prepared to manage tasks on the flight deck when workload is high and in particular in unexpected or very complex situations.

Tasks prioritization for flying, navigating and communication is harder to operationalize when there are many tasks to be performed in each category, and the tasks overlap or are queued. Furthermore, underload is also an important safety and performance problem when the pilot is out-of-the-loop.

It is well accepted by cockpit designers, pilots and artificial intelligence community that instead of trying to obtain the most of pilot performance with the least displayed information the real challenge is to provide the pilot with the most appropriate data/information/knowledge in support of each skill-based/rule-based/knowledge-based tasks at the right time.

Cognitive Computing technology could enable many advances for the pilot tasks but not all Cognitive Computing technologies match well for the aircraft cockpit operations, because they cannot be embedded in a way that produces measurable benefits to flight operations. A proactive and pragmatic approach is required to design an acceptable complementary technology to pilot cockpit operations in which both the pilot and its e-pilot support brings their own strength in organizational decision-making processes typically characterized by uncertainty, complexity, and equivocality.

It is expected that complexity could be tackled with an analytical approach with a greater computational information processing capacity, so computed based tools could extend

2405-8963 © 2019, IFAC (International Federation of Automatic Control) Hosting by Elsevier Ltd. All rights reserved.
Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2019.09.128

cockpit cognitive tasks when addressing complexity, whereas pilots can still offer a more holistic, intuitive approach in dealing with uncertainty and equivocality in decision making. This premise mirrors the idea of intelligence augmentation, in which cognitive computing systems should be designed with the intention of augmenting, not replacing, human contributions.

There are several pilot tasks that could benefit from cognitive computing support, however it is required new evaluation strategies to assess how and to which extent new cognitive computing technologies can be integrated into a flight deck to ensure that no unintended consequences emerge as a function of combining disparate cognitive computing functionalities.

Consider for example non-automated monitoring task, which is consuming pilot cognitive capacity by accessing to displayed information and interpreting the information without ambiguity. Under unexpected or very complex situations, it can generate clutter or distraction. In fact, it is accepted that even experienced pilots had difficulties using some familiar automation features accurately during unexpected events.

2. SOCIO-TECHNICAL APPROACH

The replacement of human cognitive tasks by automatisms can lead to unstable interdependencies when humans are users of the system rather than an active part of the system. Problems such as human deskilling requires a participatory approach in the design of automatisms and supporting tools through a deep analysis of feedback loops to design an appropriate sub-tasks overlapping level between the aircraft pilot (ie. human decision making) and the supporting functionalities (decision support tools), in order to achieve a dynamic stable interdependency which may evolve according to the operational context of the flight.

In this paper it is considered a socio-technical approach (Baxter et al. 2011) characterized by the interaction of one (or more) social networks with one (or more) physical networks (see Figure 1). Physical network usually can be described by a structure of components together with a set of physical laws that specify its behaviour and physical interfaces that are used for its interactions. Social network usually is a mesh of actors without any specific formal interface that responds to unwritten codes of behaviour.

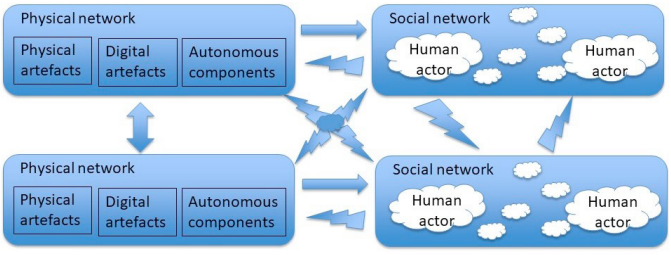

Fig. 1: Inter-relationships in a Socio-Technical System

As it can be seen in Figure 1, the interface between components of the physical network is represented by arrows, while the interface between actors is represented by a ray because there is some uncertainty when the human actor will reply and what will be the decision taken. The proper representation of the physical network and the social network together with the different types of inter-relationships is critical to implement a realistic simulation model. Note that representing the Pilot decision-making process by means of a deterministic model (i.e. automata, finite state-machine) or a pure stochastic process, will allow an easy modelling task but with unrealistic results. Furthermore, the model will be useless to get a better understanding of the hidden dynamics that can drive the system behaviour towards emergent dynamics, poor performance or unexpected system states.

Thus, it is important to realize that despite present cockpit supporting tools provides an excellent information about the state of the aircraft and the sequence of actions for each warning, it must be recognized that pilot performance requires of a proper situational awareness (SA) not only of the aircraft but also of the airspace surrounding context.

There are several definitions of Situation Awareness in the literature in Stanton (2001) but in this paper it is considered the definition of Endsley (1995) which defines SA as the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future.

For a good SA of the aircraft it has been recognized the coexistence of 3 different processes:

- Perception: This process transforms sensory cues into perceptual variables.
- Comprehension: the integration of those perceptual variables into meaningful patterns and relationships
- Projection: envisioning how the situation is likely to develop in the future provided it is not acted upon by any outside force

However, time pressure, ambiguous information, ill-defined goals, and rapid scenario changes makes the pilot cockpit SA as a not stable phenomenon: a pilot might have excellent situational awareness one moment and very poor situational awareness the next.

Furthermore, performance variability in the 3 different processes is a key factor that influence the pilot performance in the decision-making process. A small variation in the dwell time of a task probably is not a major issue, but the combination of small variations in the dwell time of different technical or human task in the cockpit can be an issue that affects the trust of the pilot on the cockpit decision supporting tools.

3. MODELING FRAMEWORK

The flexible mechanisms inherent in the cockpit to enhance pilot with different functionalities to control the aircraft for environmental and trajectory uncertainties are key to reach a stable structure with the supporting tools necessary for a safe and efficient operation.

One of the main difficulties in the modelling the decision making process in the aircraft cockpit is the coexistence of human, technical and information managing components that must be described considering a holistic approach in which the relationship between components and actors can lead to different behavioural states. Note that despite most of these relationships rely on information flows that can be traced, there are several intangible flows difficult to identify (trust, knowledge sharing, experience, training, competences) that influence drastically in the overall system behaviour.

There are several modelling formalisms to represent socio-technical interdependencies, however it is important to identify that each formalism requires a particular abstraction level that could not fit the expected level of details to identify the right component parameters or the right actor profiles required to properly understand the inter-relationships that can induce a poor performance of an aircraft pilot. In Figure 2 four modelling formalisms have been described considering the orthogonal classification features of time and abstraction level.

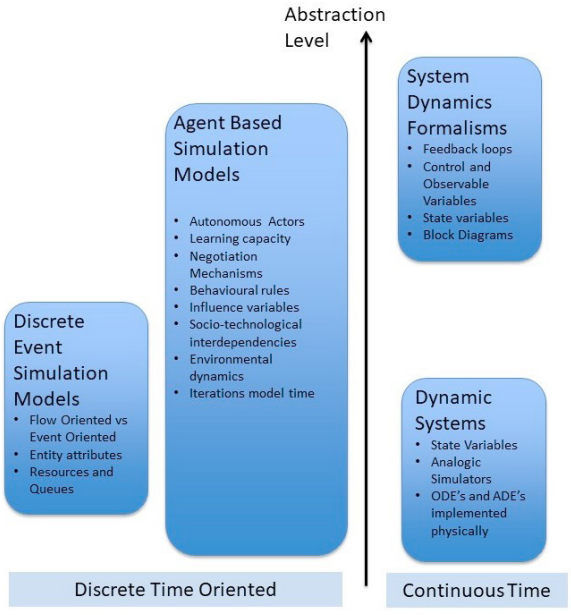

Fig. 2: Modelling Formalisms by Abstraction Level and Time Representation

An important characteristic when deciding the modelling formalism is the capacity to properly represent the autonomous behaviour of cockpit human actors. Note that cockpit supporting tools and Pilot decision making process is quite subjective and dependent of the experience, fatigue, task load, training (among others) and the characteristics of the particular operational context. Thus, in order to predict the effects of the mentioned social factors when performing a manoeuvre due to an ATC directive or to react to a separation minima infringement in a traffic scenario it is necessary to describe some actor attributes and its dynamic evolution.

Among the different dynamic modelling approaches, it is proposed the use of Agent Based Modelling (ABM) for the description of cockpit SA because it supports different types of tangible and intangible relationships connecting the three SA processes considering the cockpit architecture and in consequence provides an excellent quantitative analysis tool.

Unfortunately, the benefit of autonomous behaviours representation in ABM is also its weakness when trying to validate the implemented model. Thus, simulation results generated in ABM use to lack of traceability of the agents interactions which somehow is the main cause of lack of transparency.

To extend the proper use of ABM in the cockpit SA analysis under critical scenarios it is important to complement the modelling formalism with analysis tools to allow a proper understanding of each agent behaviour and the effects of its relationships to the overall performance of the system.

3.1 Coloured Petri Nets to enhance ABM transparency

Petri nets (PN) were presented for the first time by Petri in 1962 in his doctoral thesis as a formal method for describing computer systems. But the ease with which the PN primitives permitted the description of formerly difficult properties like concurrency, non-determinism, communication and synchronization, as well as the analysis of these properties, led to the use of Petri nets as true mathematical modelling tools. In Pizziol (2014) it is described some pilot flying task using the Petri Net formalism.

Their further development was facilitated by the fact that Petri net models easily process synchronisation, asynchronous events, concurrent operations, and resource sharing. Petri nets have been successfully used for concurrent and parallel systems and model analysis, communication protocols, performance evaluation and fault-tolerant systems.

However, one of the main shortages of Petri Net formalism to enhance ABM transparency is the lack of modelling primitives to describe the flow of information among events, which somehow is one of the main aspects to be properly modelled when describing the decision-making tasks of a pilot. Coloured Petri Net is an evolution of the Petri Net formalism which allows the description of attributes (i.e. Colours) attached to tokens.

One of the most powerful quantitative analysis tools of PN and CPN is the reachability tree in Narciso et al. (2010). The goal of the reachability tree is to find all the markings, which can be reached from a certain initial system state, representing a new system state in each tree node and representing a transition firing in each arc. The reachability tree allows (Narciso et al. (2011)):

- To identify the different system behaviours that can be reached starting from certain initial system operating conditions.

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

By analysing the different marking (Fig. 3) and the information represented, it is possible to identify those sequences of actions that can drive the pilot-cockpit system to a loss of performance. This is a very valuable information since it provides the basis for the design of new cockpit components considering downstream effects, and also enhance the component changes that could avoid a loss of performance

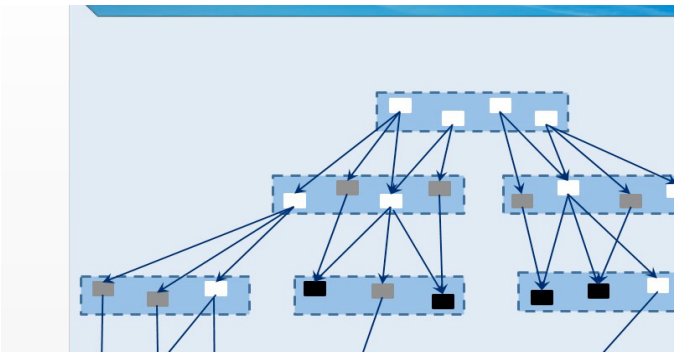

Fig. 3: Reachability Tree

In Piera et al. (2011, 2015) it is described the use of the reachability tree to validate ABM, by describing the agent behavioural-rules in CPN and analysing the behaviours that can be represented by the different interactions between agents. Thus, it is proposed to formalize in CPN the pilot behavioural rules described in the agents to trace the different feasible decisions and identify the contextual conditions that justify the loose of performance at system level.

3.2 FRAM Agent Based Modeling

Another shortage of ABM framework to describe pilot-cockpit supporting tools as a socio-technical system is a lack of standards that could be used as a guideline in the description of: Procedure, Actor behaviour, Component Behaviour and the Interdependencies.

Lack of a modelling guideline in cockpit SA is an important source of model maintenance problems when new changes must be introduced in the model to predict the impact on new cockpit functionalities. Furthermore, a lack of proper understanding how an ABM has been structured affects not only the maintenance of the model but also the acceptability and transparency of the results. To overcome these modelling shortages, it has been used the FRAM approach (Functional Resonance Analysis Method in Hollnagel (2009) which provides an excellent functional structure to represent socio-technical systems supporting different abstraction levels in each FRAM component when implemented in ABM.

In the present implementation, the human cognitive tasks have been described by means of non-linear relationships which consider static attributes and operational context to change the dynamic attributes. Behavioural rules are used also to describe the decision making process considering the dynamic attributes which guides a trade-off between performance and workload.

A functional entity is described in FRAM by the 6 following relations and represented graphically in Figure 4:

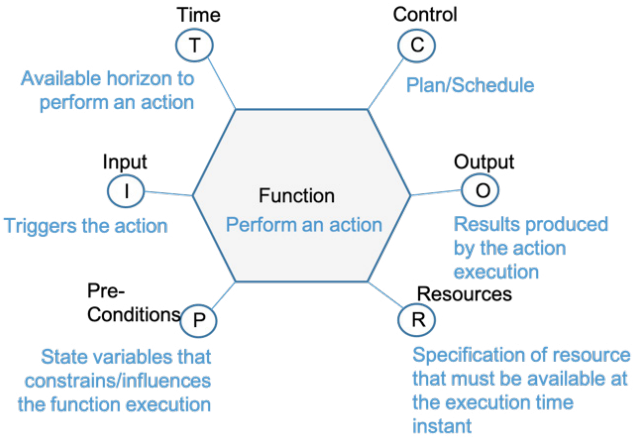

Fig. 4: FRAM Modelling Component

- Input: Triggers an action to be implemented by a computer service, a machine or by a human.
- Time: Available time horizon to perform an action. It can be immediate or with a latency in the case of computer service, or can be a stochastic time parametrized by values of influence variables in case of a human action.
- Resources: Provides an estimation of resource availability at a particular time instant, required to perform the action.
- Control: An action usually requires the adjustment of a function that can be a plan, a procedure or a human task.
- Output: The results produced by an action.
- Preconditions: State variables that must be fulfilled to proceed with the action.

Note, that FRAM approach is mainly oriented to resilience engineering, trying to determine how variability may interact within a system in a manner that leads to adverse performance outcomes.

In Figure 5 it is represented graphically, the effects of performance variability on the execution of tasks. This approach has been very useful to support a deep understanding that the overall behaviour of aircraft pilot in the flight deck. Thus, it is possible to deep in the flightdeck functional architecture to provide an answer to relevant questions such a s:

- Why the combination of safety procedures can be unsafe? The identification of the contextual

conditions that can impact negatively on safety is an excellent information to guide the changes in the pilot-cockpit procedures to guarantee that the right flow of tasks will not affect safety

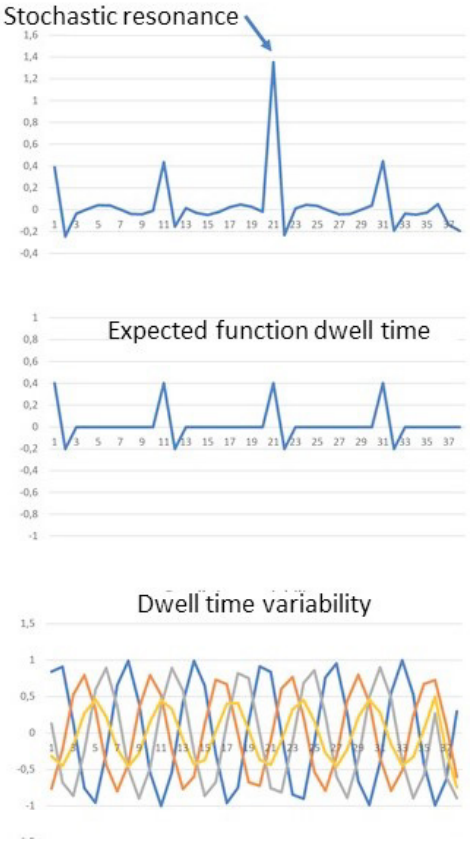

Fig. 5: Stochastic resonance due to performance variability

- Why the combination of well performed tasks can lessen the performance of the overall aircraft system? Note that if a bit of time is missed it is hard to catch up in a fast changing environment.

4. SITUATIONAL AWARENESS ABM

By considering socio-technical systems as an integrated whole, the multidimensional aspects of performance can be understood through a broad system view, requiring a modelling paradigm to describe the interrelationships between components that allow to spread by augmentation any disturbance introduced (i.e. environment) or generated in the system. Furthermore, the proper representation of socio-technological component dynamics and its interdependencies will allow to identify inherent mitigation mechanisms that isolates certain inter-relationship dynamics and could be used in the re-design of the cockpit architecture for a more robust SA supporting system.

The complexity of the cockpit components considering the socio-technological aspects of its architecture calls for a holistic modelling approach that employs multiple modelling paradigms to benefit from their modelling features while avoiding their shortages. In Table 1, it is summarized the modelling benefits of the modelling paradigms proposed.

Table 1: Modeling Paradigm benefits

ABM	FRAM	CPN
Coexistence of Technical and Social dynamics Mesh of actors Agent behavioural rules to represent complex system behaviour	Structured Modelling Coexistence of Technical and Social characteristics Analysis supporting tool. Feedback loops	Causal Modelling State Variable formalism Validation tools Design of mitigation policies

The human behaviour is strongly related to the type of the Activity to be performed. According to the Activity nature, the person dynamically triggers the available cognitive resource and regulates their consumption properly. The so-called Skill-Rule-Knowledge framework in Rasmussen (1986) or the Hierarchical Task Analysis in Mamessier (2016) describes clearly how the cognitive resources demand and activation is determined by the ongoing activity and bring to different types of behaviours (Figure 6):

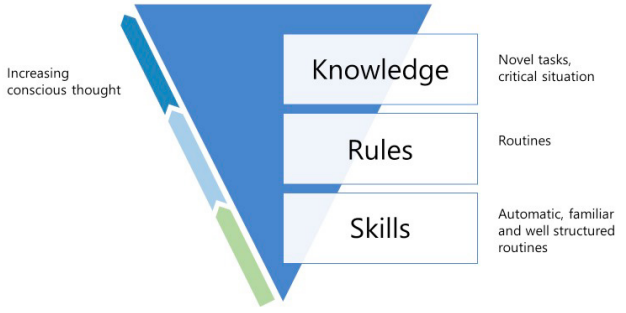

Figure 6: Behavioural patterns and type of tasks in the SRK model

- The less demanding behaviours in terms of cognitive resources and active control are the well-established routines, carried out on the base of consolidated patterns called skill-driven behaviours. Typical examples of this group of behaviours can be found in the daily usage of information technology.

- More complex activities that, even regular, need for the active person's involvement and more cognitive resources to be handled are the rule-drive behaviours.

- When the situation is novel or critical or very complex, the highest cognitive resources, including the problem solving and decision making, support the knowledge-driven behaviours, often oriented to elaborate new behavioural solution

The great part of pilot tasks is skill based, so it important to take in consideration that the same cognitive resource may attend different tasks, affecting the availability of the resources making them less persistent and effective. Moreover, they shall vary on the base of both the personal factors (e.g. age, expertise, etc.) and the socio-cultural ones. It is easy to note, that an actor with a high seniority and expertise will allow to simulate some rule-tasks as skill-tasks which will have a lower impact on the mental workload with respect to an actor with lower seniority and expertise which will have a higher mental workload demand to perform rule-based and knowledge-based tasks. Different non-linear relationships has been considered to describe dynamically the triple tight-bound between pilot profile, contextual information and dynamic attributes.

In Figure 7 it is represented graphically the mental resources considering the socio-technical approach. One of the main modelling targets in ABM is to try to emulate the time variability of the pilot tasks by properly representing the SA and the tasks load considering the contextual conditions. Thus, when a pilot is performing monitoring functions and a conflict is detected the required mental resources will be different if at the same time is evaluating a warning in the ECAM (Electronic Centralized Aircraft Monitoring) system

Fig. 7: Mental resources required to perform cognitive tasks

Additionally to the mental resources, some behavioural rules are also implemented trying to represent the dwell time variability when performing a task , and also the performance of the task.

The active attitude is also a precondition of performance in interaction with the automated tools: when actively involved in defining the state of the system, pilots have a clearer mental model and awareness of the system state than when they are passively monitoring.

Causal rules are implemented as agent behavioural rules collecting past experiences and well accepted knowledge to introduce variability in the expected performance of the pilot tasks

5. CONCLUSIONS

It is well accepted that airspace capacity depends on the performance of human factors (air traffic controllers and aircraft pilots). In order to minimize the variability of the tasks consumed when performing tasks, pilots (also controllers) have been enhanced with supporting tools to automate some tasks providing more deterministic performance while extending their availability to attend incoming events.

Most simulators consider mainly the technical part of the traffic, while some attempts to consider the role of humans has also been reported considering the variability of the tasks according to stochastic processes. The proposed methodology try to provide a better understanding of pilot-cockpit performance variability according to the supporting tools.

An extension to present model is to determine which tasks are capable of being assigned to the cockpit automatisms, and in what way, such that the pilot remains in overall control.

ACKNOWLEDGEMENTS

This research is partially supported by the H2020 CS2 Project: E-PILOTS (GA 831993) and the national Spanish project: “EU-TM” (ref. TRA2017-88724-R). Opinions expressed in this article reflect the authors’ views only

REFERENCES

Baxter G., Sommerville I. (2011), “Socio-technical systems: From design methods to systems engineering”, Interacting with Computers, Vol. 23,1, pp. 4–17.

Endsley M. (1995), "Toward a Theory of Situation Awareness in Dynamic Systems," Human Factors, 37.

Hollnagel.E (2009). The ETTO Principle: Efficiency-Thoroughness Trade-off: Why Things that go Right Sometimes go Wrong. Ashgate Publishing Ltd.

Mamessier, S., & Feigh, K. M. (2016). HTA-Based Tracking of Pilot Actions in the Cockpit. In Advances in Physical Ergonomics and Human Factors (pp. 93-103).

Narciso M., Piera M.A., Guasch A. (2010) “A methodology for solving logistic optimization problems through simulation,” *Simulation*, vol. 86, no. 5–6, pp. 369–389.

Narciso M., Piera M.A., Guasch A. (2011), “A time stamp reduction method for state space exploration using colored Petri nets,” *Simulation,* vol. 88, no. 5,

Piera M., Music G. (2011) “Coloured Petri Net Scheduling Models: Timed State Space Exploration Shortages”. *Mathematics and Computers in Simulation*,. V 82 (3).

Piera M.A., Buil R., Ginters E. (2015). State space analysis for model plausibility validation in multi-agent system simulation of urban policies. *Journal of Simulation*

Pizziol, S., Tessier, C., & Dehais, F. (2014). Petri net-based modelling of human–automation conflicts in aviation. Ergonomics, 57(3), 319-331.

Rasmussen J. (1986) “Information Processing and Human-Machine Interaction: An Approach to Cognitive Engineering”. *New York: North Holland*,

Stanton, N. A.; Chambers, P. R. G. & Piggott, J. (2001) Situational awareness and safety. Safety Science 39