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Development of a Multi-Factorial Instrument for Accident Analysis Based on Systemic Methods

C. V. Pietreanu, S. E. Zaharia, C. Dinu

Abstract**—**The present research is built on three major pillars, commencing by making some considerations on accident investigation methods and pointing out both defining aspects and differences between linear and non-linear analysis. The traditional linear focus on accident analysis describes accidents as a sequence of events, while the latest systemic models outline interdependencies between different factors and define the processes evolution related to a specific (normal) situation. Linear and non-linear accident analysis methods have specific limitations, so the second point of interest is mirrored by the aim to discover the drawbacks of systemic models which becomes a starting point for developing new directions to identify risks or data closer to the cause of incidents/accidents. Since communication represents a critical issue in the interaction of human factor and has been proved to be the answer of the problems made by possible breakdowns in different communication procedures, from this focus point, on the third pylon a new error-modeling instrument suitable for risk assessment/accident analysis will be elaborated.

Keywords**—**Accident analysis, multi-factorial error modeling, risk, systemic methods.

I. Introduction

THE characteristics of interactions between components or factors influencing safety involve high levels of risk that reflect in producing a sequence of events (effects) that cannot have elemental or easily accessible causes.

In linear methods, the spectrum of barriers is modeled as position and size variables, representing defense procedures against individual errors/deficiencies [2], whilst for nonlinear methods, reductionist approaches like system decomposition do not work.

Linear analysis methods, which may be sequential, epidemiological, etc., study the causes of an event and outline the scenario of the accident either with the purpose to improve the reliability of weak components or to implement/strengthen system's barriers. The transition from linear or complex linear succession of events to systemic models that describe accidents from the perspective of the loss of control presumed introducing new diverse sequences of the analysis after exploring the base levels of safety, with the main objective to maintain the balance/stability in aviation systems.

The traditional focus of analysis described accidents as a sequence of events (sequential models) or concatenation of current and latent conditions (epidemiological models) [6].

In the 1980's, the foundation of system theory has been developed by Leplat, presenting in the Journal of Occupational Accidents the guidelines of system approach for accidents, emphasizing system changes that led to accidents, thus outlining the interconnections between the indicators of dysfunctions [3]. Latest models describe the processes evolution related to a specific (normal) situation, making a parallel between emergent phenomena, normal performance and failures [9].

Criticisms on different methods indicated over time that none of the existing ones answer to all the issues that can be raised. The idea that a perfect analysis method has not been created was tenuously outlined since Reason developed the Swiss Cheese model. The argument that the method did not take into account the interdependence of causality factors (thus the results may be too vague to have significant practical use) was considered ungrounded since the method has not been developed to provide a detailed analysis of accidents. This justification confirms though that the limitations of this method are considered specific to linear analysis. Further developments of complex linear methods and nonlinear ones, resolved some of the matters by taking into account links between the factors involved, but the main problem that remained unsolved was the practical use of theoretical models, more so in the case of the systemic ones. As some authors note, irrespective of the type of methods (i.e. linear or non-linear), the research of the causes of an event may imply application of several accident models as they can work together to shape the accident scenario and discover its root causes [4].

Throughout this paper, the authors will emphasize that since different methods could have different areas of application or highlight certain problems, their practical applicability might not cover all the factors and risks that describe the scenario of accident occurrence.

II. Limitations of Systemic Methods

When the methods are also used for a thorough retrospective analysis of accidents, the study must be preceded by an essential preliminary step in shaping a rigorous analysis, consisting in describing the system and understanding the link between the factors involved in the occurrence of an accident.

The cornerstone of systemic methods can be found in the descriptive aspects of errors associated to human performance developed in the system's theory of Rasmussen [5], and although these matters are addressed differently in the

C. V. Pietreanu, is with the Faculty of Aerospace Engineering, Polytechnic University in Bucharest, Romania, Gh. Polizu Street 1-7, Sector 1, Bucharest, 011061 (corresponding author, phone: +40742046405; e-mail: casandra.pietreanu@upb.ro).

S. E. Zaharia and C. Dinu are with the Faculty of Aerospace Engineering, Polytechnic University in Bucharest, Romania, Gh. Polizu Street 1-7, Sector 1, Bucharest, 011061 (e-mail: sorin.zaharia@upb.ro, cornel.dinu@upb.ro).

mentioned methods, the desire for improvement in accident analysis grew into a necessity for multi-factorial error modeling development.

The FRAM model realizes complex interactions and close couplings by connecting six functions (i.e. Time, Inputs, Outputs, Preconditions, Resources and Control) in a node [7], [27]. It does not focus on the role of safety management constraints and it does not take into account adaptive control structures that can be embedded in the system itself.

The Functional Resonance Analysis Model will be considered the basis for the authors' further analysis.

In the context of variation of functions which have an influence on the outcomes of processes, normal performance becomes a matter of adjusting different actions; thus, errors or failures are not the attribute of specific causes, but of the interaction between them, since the root cause of errors cannot be retrieved in normal actions [6].

A complete way to depict "Control" in the FRAM model can be addressed as in the System-theoretic Analysis Method and Processes analysis. The method developed by Leveson describes a feedback-based control hierarchy limited not by imposing barriers, but by applying restrictions to the considered variables of the system [27]. This approach on control through restrictions or barriers implies maximizing the non-linear function (i.e. performance of human factor), considering different variables and non-linear restrictions.

$$F : \mathbb{R}^n \to \mathbb{R} \tag{1}$$

$$F = f(x_1, x_2, \ldots, x_n)$$
$$\max\{F(X) \mid c_i(X) = 0, i = 1, \ldots, m^{'}; c_i(X) > 0, i = m^{'} + 1, \ldots, m\} \tag{2}$$

F(X) - function needed to be maximized (performance of human factor), x - variables of the function (system)

$$h_i(X) = 0, \quad i = 1, \ldots, m^{'} \tag{3}$$

$$g_i(X) > 0, \quad i = m^{'} + 1, \ldots, m \tag{4}$$

The necessity of a more structured approach, superficial evaluation and usability assessment [12], also the lack of guidance for application criteria due to the methods qualitative approach and a considerable extension of the analysis are the highlighted limitations of systemic models.

It is considered that last generation of systemic models requires a wide range of knowledge on the interrelations between the causal factors [8], but considering that critical analysis on linear methods targeted the exact problem of not taking into account interactions between analyzed factors, a development of accident modeling must not mirror the problems in applying non-linear models, but rather their drawbacks [27].

Though the efforts made over time to extend existing PRA techniques to complex management problems or elaborated software activities have failed [14], the development of the latest systemic models (e.g. STAMP model) can overpower this risk assessment issue [27].

The application on such methods is very useful considering a scholastic approach; they can also provide good results in research, but they must not be considered to replace the analysis made by investigators by collecting data and evidences in a technical analysis. Therefore, a reliable manner to initiate the research of an accident through linear/nonlinear analysis is by studying the final accident investigation report.

A correct approach of accident analysis methods is to consider them a great tool to research all the factors that outline the causes of accident, indicate and categorize different classes of risks, and determine the links between elements, this way acquiring more information. Surely, an important number of models can also be used as a risk assessment tool through a proactive approach.

The most common comment on FRAM model makes reference to its applicability and the fact that it has been mainly depicted in the literature [20] and since only some of the important aspects of system's theory are clearly addressed in FRAM analysis [12], these ascertainments can become a starting point for improving the method and developing new directions.

Considering an extended approach to Functional Resonance Analysis Method, through a detailed examination of the six functions, a conclusive solution to the model's drawbacks may be provided through a synergistic way.

After studying the literature, analyzing the strengths and weaknesses of systemic methods, in particular FRAM model, a research was made at investigation and safety analysis centre concerning the practical applications of non-linear models. This way, the authors were able to make their own observations/considerations and identify a series of elements that could improve accident analysis. One of the most important factors that were taken into account (the communication) will be widely studied in the following chapter.

III. A Systemic Approach on Accident Analysis. Establishing New Directions

Factors that influence the crew's actions or inactions, whether it is the procedures used, instructions received, etc. can define a critical situation and the circumstances of the accident. Critical analysis of these circumstances will result in the discovery of risk factors and their nature.

Since not all of the system theory important concepts are represented in the FRAM model, the following analysis will consider communication as one of the most important factors on which the attention must be focused.

Communication is a critical issue in all aspects of human interaction, essential for organizational and managerial performance in the aviation environment [22] and is reported to be the major contributing factor to aviation accidents [23]. Through communication, other factors are realized/made possible (e.g. information gathering and sharing, planning, decision-making or identification of errors and problems) [24].

Surely, communication can be represented in a FRAM function, but considering that it can be involved in all of the elements of the functional resonance analysis (i.e. input, time, control, preconditions, resources and outputs) or in all the functions that can be connected through the analysis of an accident, communication will be considered a common factor for/above all the elements considered in the research.

A FRAM function refers to the process/task/activity that must be performed to produce a certain outcome, so it represents the means necessary to reach stipulated goals [21], but seeing that communication can be a ubiquitous factor in all the aspects regarding human interactions, the analysis will be based on a different approach.

Interpersonal communication factors have been implicated in up to 80% of all aviation accidents [25] and 60-80% of incidents and accidents are caused by human error due to ineffective communication [26], so it must become a central point in an improved accident model.

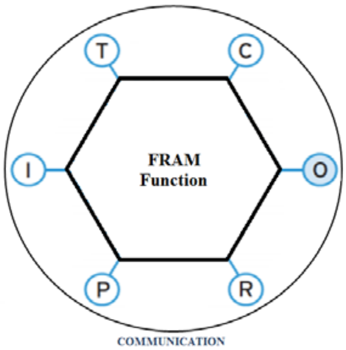

Fig. 1 Importance of communication in the FRAM functions

Due to the need to connect the elements from a node, the above discussed element (i.e. communication) will be considered an additional part of a function.

The new multi-factorial instrument for accident analysis developed throughout this paper will impose and adjoin a significant complementary element to the node characteristic to the Functional Resonance Accident Model. This is considered imperative for establishing the importance of communication (as a critical aspect in the interaction of human factor) in the explored processes.

This research aims at assessing the defining elements of the heptagon function, trace hypothesis for identifying deficiencies that may be preconditions for an accident and consider the variation of functions/performance which influences the outcome of actions/processes. The sequence of actions will be explored considering the initial circumstances/critical events that reflect a neglectful check, an improper action or an erroneous decision.

The first piece of the analysis is the implementation of a function that will be attached to specific elements of the analysis (a Functional Resonance Accident Model node). In this manner, the six focus points (that need to be examined in order to understand the causes of an accident) of the hexagon of FRAM analysis, will turn into a heptagon, whose seven elements will meet the exigencies of a modern research and will define the elements on which the attention must be focused [1], [27].

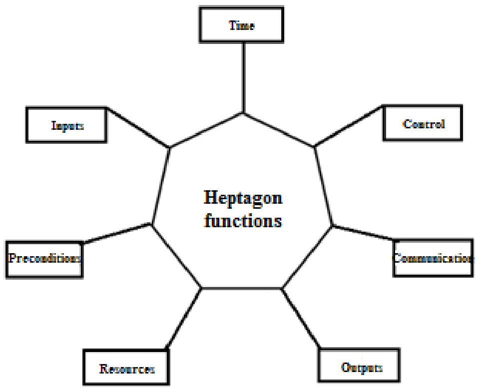

Fig. 2 Representation of the heptagon function [27]

The critical analysis that will be conducted further will indicate the importance and significance of the functions set and will establish a hierarchy, which will highlight the fact that certain processes can sometimes be formal. For example, in some analyzes, time is relevant only by indicating the evolution of other conditions or the interactions between them.

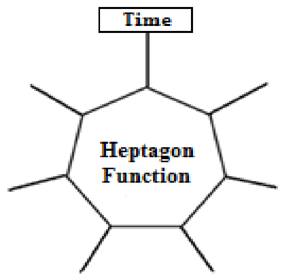

Fig. 3 Representation of "Time" in the heptagon function

Time indicates aspects that concern the way the function is carried out [21] and can indicate the moment an error/defect produces, in which case, its location in a set of functions is somewhat formal, important just to maintain the rigors of an analysis. However, the indications on the period that preceded a corrective action, or the length an omission/inaction or violation of rules, can provide valuable information on the reasoning/motivation behind the produced event. It can also provide references to other functions (e.g. the lack of communication between ATC and pilots, the identification of incorrect/incomplete or distorted messages, etc.) [1].

The seven elements corresponding to a heptagon highlight the profile of deficiencies and directions included in the analysis, produced errors and defects, conditions that preceded a given situation and instances that build the nature of the immediate impact. Thus, the cornerstone of the developed model is the systemic approach on errors and an extended analyze of the arising conditions, outlined by negative aspects concerning the consequences; and positive ones that may provide opportunities and the prospect of a breakthrough in the aeronautic industry [1].

Constraints imposed by restrictions defining functions that build a node, dictate the applicability of guidelines, plans and procedures or communication channels relevant for control efficiency.

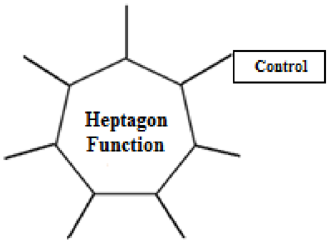

Fig. 4 Representation of "Control" in the heptagon function

In the development of events from the incidents/accidents category, there may be information or indications that will facilitate the comprehension of not complying conditions or exceptional actions. These symbolize poor control, but useful for maintaining intangible or symbolic barriers, reflecting the constraints imposed to physical actions. In this sense, the proposed analysis will consider the following types of operative barriers, applicable to different conditions.

Taking into account the processes carried out, control is a complex non-linear element of the analysis and a cornerstone for eliminating deficiencies which may come from inadequate management and achieving high levels of safety and performance. As stated by the International Civil Aviation Organization in the Human Factors Guidelines for Safety Audits Manual [17], control maintains risks at low levels; hence deficiencies in control in the organizational culture lead to chaos [13]. In order for the fault (i.e. loss of control) to occur, the following input events must be produced.

Considering: LOC = Loss of control, AC = Abnormal conditions, FOC = Failure of control then:

$$P(AC) \cap P(FOC) = P(LOC) \quad (5)$$

If the events describing abnormal conditions and failure of control are considered compatible dependent events, the intersection probability will use conditional probabilities:

$$P(LOC) = P(AC \mid FOC)P(FOC) = P(FOC \mid AC)P(AC) \quad (6)$$

It is considered that safety is a matter of control and if accidents occur then there is no control of the interactions between the system components [10]. In Functional Resonance Analysis Method, "Control" refers to monitoring, supervising or regulation of the procedures/functions [9], [21] but in this method, elements like Control, Preconditions or Resources, do not solve the issues created by the one element considered to be the main contributing factor in aviation accidents (i.e. communication).

TABLE I
CFIT RISK RELATED TO HUMAN FACTOR (COMMUNICATION) [15]

Risk type	Value (%)
Communication environment	12

Communication, including the language used, the terminology and the environment, are examples of frequent sources of hazard in aviation, considered to be conditions that reduce the ability to perform a prescribed function [18]. According to IATA statistics, communication which is essential for organizational performance is the major cause for errors during a flight. 20 % of in-flight errors are due to this basic safety requirement (i.e. communication), the percent being divides between different flight phases. While the highest percentage (43%) of communication errors occur during landing procedures or approach, considering the communication between pilots, this factor involves 8% of loss of control in flight [16].

TABLE II
FLIGHT CREW ERRORS [16]

Flight crew errors	Percent of LOC accidents (%)
Pilot-to-pilot communication	8

In the mid-1990s, a crew information requirements analysis (CIRA) was developed and internally applied by Boeing in safety analyses in order to describe how crews acquire, interpret, and integrate data into information. This was a tool to determine and understand what were the bases of the crew's actions and the reasons why they failed to understand a sequence of events [19].

Complex emergent factors entail the implementation of barriers with the scope to control changes in the levels of safety, impose restrictions and block errors [11], [27]. Surely, barriers can be represented by some of the analyzed elements in a heptagon (i.e. communication in the form of the information or data received from air traffic controllers), or control which may be represented by pilots corrective actions, awareness of a dangerous situation, a proper understanding of unusual circumstances, or multiplying safety systems (e.g. visual warnings) through redundancy. However, critical incidents may occur despite application of barriers, by considering the lack of control.

The intangible barriers considered, monitor factors that contribute to errors and, through a proactive mechanism, will exclude the possibility of overcoming acceptable ranges.

Considering the need to enhance safety in the operational context, communication, either verbal or non-verbal shall outline a conductive environment characteristic to the specificity, efficiency and accuracy of the aeronautical environment. The channel described must represent a good environment to identify deficiencies in communication and for executing the processes that require imposing barriers to ensure and maintain quality control. These elements must be grounded on the culture of information which requires knowledge, so the human factor as an integrated part of the operations, must recognize and report auto-generated or external factors which can affect situational awareness and judgment [13].

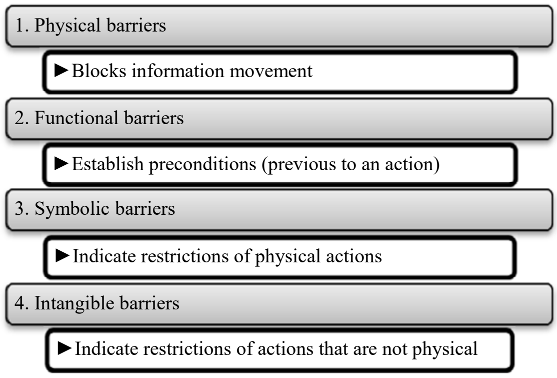

Fig. 5 Barriers of the analysis

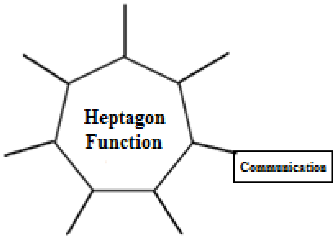

Fig. 6 Representation of "Communication" in the heptagon function [27]

TABLE III
CONVERSION OF SAFETY CULTURE CHARACTERISTICS REGARDING COMMUNICATION [17]

Old model	New model
Closely held information	Open communication

Isolation of characteristics that can lead to poor/inadequate decision making (through communication that indicates gaps in training) annuls dependence on training or education, predisposition, or even emotions or health and can definitely improve human performance.

Whether we are talking about radio communication between the crew and air traffic controllers, checklists, etc., these procedural errors are mirrored by incorrect or faulty communication. Thus, the implementation of crew resource management concerning human factor interaction in general with a focus on communication and verification represents the answer to optimizing the issues related to information/safety culture [13], [27].

In the manner of the above described directorates, control actions will be outlined by the usefulness of communication fixed as a subset on processes and control actions [1].

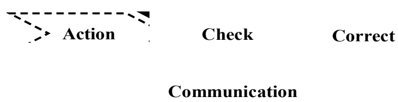

Fig. 7 Sequence of control actions and communication (in subset)

The inability to discover errors is triggered by an improper check or by improper actions, but can be limited by imposing control/barriers. The starting point of the research will consider normal (standard) conditions of flight, but for a correct and complete description of the accident scenario, assessment of system performance will also regard achieved performance which may reflect in inactions, instructions that were not followed/or have not been correctly realized, and actions taken to adapt to an abnormal/exceptional situation, hence, will reflect in low levels of safety.

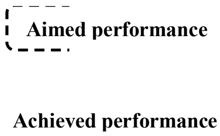

Fig. 8 Accident scenario (Aimed vs. Achieved performance)

In relation to the dynamics of the system analyzed, the factors that will be considered do not involve eminently comparison with a flight of which characteristics are considered "normal".

The context or framework within which are imposed and implemented processes/procedures to be reported, may have appreciable variation reflecting the knowledge level, skills, competencies, training or adaptability on the one hand and, on a higher level, safety and group culture.

The new multi-factorial instrument for accident modeling will explore and evaluate the next classes of procedures and conditions [1], [27]:

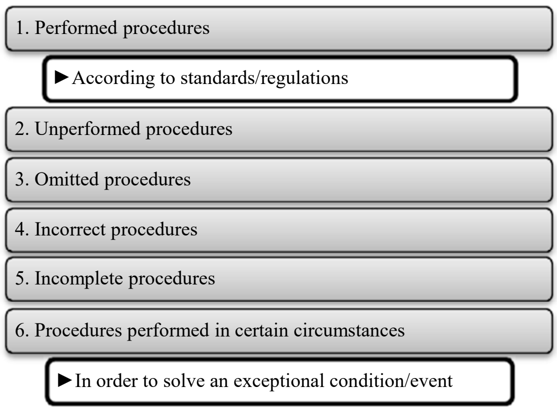

Fig. 9 Types of procedures considered in the analysis

It should be underlined that the omitted procedures represent a special class, with low probability and frequency, but worth considering for a rigorous definition of the model and the exceptional cases involving the intent on which inaction is grounded and, extrapolating, the presence of psychiatric disorders.

The last class of processes under analysis establishes actions specific to human factor, but those imposed by an abnormal context or by circumstances for which the crew was theoretically prepared. These actions may suffer changes compared to those presented in the previous simulations so it is worthy to take into account the impact on pilots (and the staff involved) and how they react and adapt to new situations/issues [1].

In a specific context, a number of psychological factors, emotional or health states highlighting fear, or in contrast, a sense of responsibility, self-control, flexibility, skills, ease of adaptation to extreme situations, ability to understand these issues and also having performances under stress can be analyzed [1].

Another aspect involves a good knowledge of processes, standards and imposed rules and a sufficient low reaction time. However, these situations are difficult to measure and control, requiring additional efforts to identify, understand, estimate and to establish a linear predictable behavior.

Because a pattern cannot be established, resources used to cancel the psychological implications can sometimes be in vain; the most difficult instrument of the analysis refers to the actions taken under the dome of psychological factors, actions that may be abnormal, illogical, improvised, that can be balanced or annulled by situational awareness and imposing barriers [1].

During development or after the examination of the heptagon functions, a number of deficiencies or various kinds of operating errors can be determined, which sometimes may reflect in the lack/drawbacks of regulations or violation/ unawareness of rules.

In the heptagon functions, one or more elements corresponding to nominal parameters (ex. inputs, time, etc.) or triggered elements (ex. communication, control, etc.) can be identified.

The way to connect the elements and functions of the heptagon can imply a linear method (i.e. each output of the function can become an input which will be processed for the successor node), creating in this manner connections for the processes explored [1], [27].

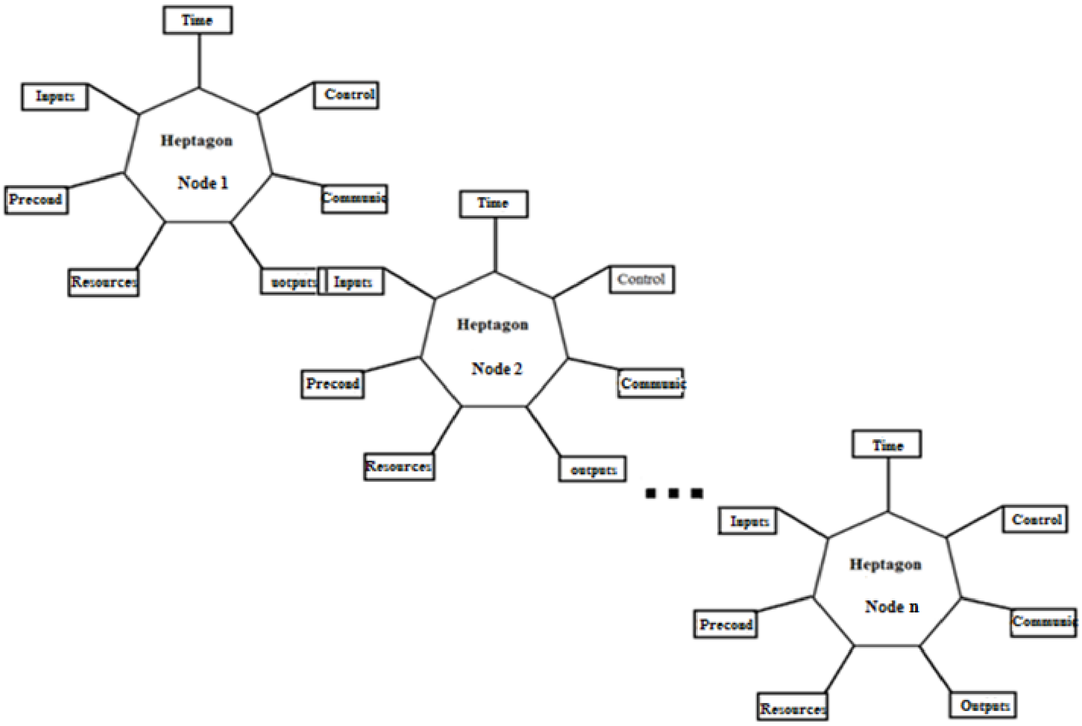

Fig. 10 Linear connection of heptagon functions [27]

Identification of normal variation is a challenge especially for the early stages of the analysis, but a structural approach based on connecting multiple configurations is suitable for collecting, evaluation of data and understanding dependencies.

The systemic (non-linear) approach of the accident analysis implies though distinct coupling mechanism for the heptagon functions, where connections of elements are made in a manner that does not involve constraints and, for example may link communication from one node to time, or to lack of control of another node [1], [27].

The proposal of this improved instrument can solve the problem of restricted and limited application in safety analyzes and technical investigations, as subsequent developments aim precisely these instructions and useful guidance to unravel different aspects of the analysis, imposing tangible perspectives and support strict and proposing a systemic approach on aviation events and a better relationship between researchers and investigators.

At the end of this research process, a review of the characteristics and issues worthy of consideration for a brief exposure of the grounds of shaping the analysis was achieved, pointing this way innovation, strengths of the method and the need to implement it.

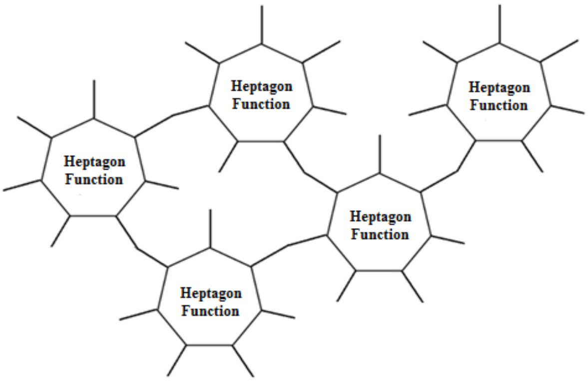

Fig. 11 Coupling mechanism for heptagon functions [27]

IV. Conclusion

Improving safety levels can be done after studying the variation of functions and the interdependencies between different factors, thus after performing an analysis of the system as a whole.

A systemic approach to errors, emphasizing the profile of deficiencies of the directions included in the analysis, excluding the redundant tendencies of elements that are not relevant or important and explaining the performance variation perspective are elements that must be kept on a good multi-factorial systemic analysis.

This research has emphasized the limitations of linear and nonlinear accident models, with a focus on the systemic FRAM model. Discovering the drawbacks of the systemic models has become a starting point for improving methods or developing new directions to identify risks

The proposed instrument for accident analysis is built on two theoretical pillars: system theory and control theory, and it implements a succession of concepts and notions from the exact sciences class: mathematics, physics (useful for the engineering aspects contoured by the conducted analysis), but also social and psychological aspects related to learning capacities and mechanisms and human actions and decisions implementing [1].

The model is also suitable for risk analysis (both a qualitative and quantitative approach), since it can develop a way to evaluate different classes of risk, evaluate them and calculate the probability of accident occurrence.

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