Tenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2013)

Performance based approach to investigate resilience and robustness of an ATM System

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***Abstract*— Resilience is a fundamental property of the natural ecosystem that enables quick recovery after numerous disturbances occurring frequently. This vital ability of the ecosystem makes resilience a very desirable property of man-made socio-technical systems. The European ATM System, which in future will be set up to achieve the performance targets given by SESAR, is such a socio-technical system. A lot of contradictory definitions of the term resilience in different domains fall into two big categories with semantical meanings of „resilience“ or „robustness“. Currently, in the ATM Context exists a definition of resilience from the safety science perspective only. This paper will apply a new definition of resilience and robustness on the ATM System to help realizing the agreed performance targets under the influence of disturbances. To follow this approach, a clear differentiation between both terms has to be carried out.**

The aim of this conceptual paper is to present a developed framework that incorporates concepts of robustness, resilience and relevant terms such as disturbance, stress and perturbation. This is complemented by an according decision-making chain. Furthermore, this paper suggests some qualitative and quantitative forms of measures of resilience and robustness and provides a structured approach for the investigation of both terms. By incorporating the presented terminology in order to identify new methods to increase resilience or robustness, a new modeling approach will be introduced. This will be complemented by an according algorithm. The structure of the modeling approach divides the ATM System into two - a sociological and a physical dimensions. The sociological dimension shall enable to reveal improvement potential in the context of operational rules of particular stakeholders, adapting resources and finding alternative ways to achieve the given performance targets.

Keywords - performance; resilience; robustness; ATM System

I. Introduction

A. Paradigm of the future ATM System

The realization of the performance targets set by SESAR [19] incorporates the incremental step approach of three operational phases. This encompasses the time based operations, trajectory based operations and performance based operations, which are aligned with the SESAR definition of the service levels 2, 3 and 4. The third operational phase, performance based operations, aims to implement an „European high performance, integrated, network-centric and collaborative and seamless air ground ATM System“ [19]. To achieve the performance goals, network operations will be planned collaboratively, using a system wide information management. Performance based operations of the ATM System can be seen as the method of resolution to realize the political and socio-economical expectations of the ATM System in future.

The ATM System as a socio-technical system is driven by economic interests of the participating stakeholders. Hence, it is performance oriented. Its performance is evaluated by means of key performance indicators, which are, for instance, delay, throughput, punctuality. Key performance indicators, defined by ICAO, are assigned to 11 key performance areas [14]. „KPAs are a way of categorizing performance subjects related to high-level ambitions and expectations“ [14]. Disturbances like the hurricane Sandy, which in 2012 caused massive disruptions in the air transportation systems, not only in North America but also in Europe, affect the continuous realization of performance targets. Generally, disturbances deteriorate the performance of the ATM System, which state expressed by performance indicators undergoes undesirable changes. By means of investigating resilience and robustness as system properties, one is able to mitigate negative impacts on performance.

B. Aims of the paper

This conceptual paper intends to discuss a new methodology to realize the implementation of the SESAR performance targets by means of increasing resilience or robustness of the ATM System. The potential of resilience and robustness allows decreasing the impact of disturbances, so that either the system is capable to return faster to its prior performance specifications or to remain within its given performance boundary settings. To foster the properties of resilience and robustness, clear definitions of both terms have to be made. To the best of the authors knowledge, to the present day the application of resilience and robustness on the ATM System is used intuitively and with respect to resilience, limited to safety aspects [12], [4]. In this paper a methodology will be presented that extends the safety dimension of resilience.

Because of the universal character of the methodology with respect to the characteristics of socio-technical systems, it can be applied generally or at specific subsystems of an ATM System as well. Therefore it enables investigating resilience and robustness at different levels of detail as well as at different scales of

This work is supported by the European FP7 Project „Resilience2050“ funded through the FP7 AAT Call 5, topic AAT.2012.6.2-4. See http://cordis.europa.eu/projects/home_en.html or http://www.resilience2050.eu

expansion of an ATM System. A further important point in the presented approach is a proposition how to measure resilience and robustness, since if they are not quantifiable they are not improvable.

To develop a performance based approach how to investigate resilience and robustness by applying the new terminology, this paper shows a modeling approach, which focuses on the abstraction of the system in the form of stakeholders on the one and the movement of the aircraft on the other hand. To connect these both dimensions the pilot serves as a combining element. Following the modeling approach, an algorithm will be determined that summarizes necessary steps, which have to be performed when investigating resilience and robustness. The emphasis on the sociological dimension of the modeling approach shall enable to reveal improvement potential in the context of operational rules of particular stakeholders, adapting resources and finding alternative ways to achieve the given performance targets.

C. *Structure of the paper*

The paper is broken down into five chapters. Chapter 2 investigates existing contradictory forms of definitions of resilience and presents a framework, which incorporates a concept of interdependencies between robustness, resilience and other relevant terms. In the next chapter a suggestion how to measure resilience and robustness will be presented, addressing the sociological aspect of the ATM System by means of the according decision-making chain. Chapter 4 discusses a performance based approach how resilience and robustness should be investigated. The last chapter summarizes results of this paper.

II. Resilience and robustness in the ATM Context

A. *Forms of defining resilience*

The term resilience has been introduced first by Hoffman [9] in the field of mechanics and material testing in 1948. One decade later Holling [10] implemented the term in ecology. Currently the topic of resilience is widely spread and extensively studied. Up to the present time plenty of papers and books have been published on resilience, covering different research domains. For instance, the works of [3], [7], [9], [10], [11], [12], [16], [17], [20] serve a good representation of the various interpretations or forms to define resilience. In the different research domains, this forms have been termed as „engineering resilience“, „ecological resilience“and „resilience engineering“.

The *first form* - „engineering resilience“ - defines resilience as the time required for a system or as the ability of a system or as the capability of a substance to return to an equilibrium or steady-state or original state, following a disturbance or some time later after the removal of the disturbance factor [9], [16], [11], [7]. It should be noted that Hoffman [9] uses the term „resiliency“ to describe this inherent ability of a substance whereas under „resilience“ a more extensive property which takes into account the size and shape of the object as well, is formulated.

The *second form* - „ecological resilience“ - determines resilience as the ability or as the capacity of a system to absorb a disturbance, whilst essentially retaining the same function, structure, identity and feedbacks [10], [11], [7], [20], [3].

Oxford Dictionary [15] gives the following definitions of the terms „resilient“ and „robust“:

resilient (adjective)

- (of a substance or object) able to recoil or spring back into shape after bending, stretching, or being compressed;
- (of a person or animal) able to withstand or recover quickly from difficult conditions;

robust (adjective)

- (of an object) sturdy in construction;
  - strong and healthy; vigorous;
  - (of a system, organization, etc.) able to withstand or overcome adverse conditions;
  - uncompromising and forceful;
- (of wine or food) strong and rich in flavor or smell.

Hence, it may be stated that „engineering resilience“ tends semantically to resilience and „ecological resilience“ inclines to robustness. A well structured overview on robustness or „ecological resilience“ can be found in [3].

The *third form* - „resilience engineering“ - has been introduced by Hollnagel et al. [12] in 2006. It investigates human and organizational aspects with regard to the design of safety critical socio-technical systems [12]. „Resilience engineering is a paradigm for safety management that focuses on how to help people to cope with complexity successfully when exposed to pressure“ [12]. In the White Paper on Resilience Engineering for ATM, in 2009 EUROCONTROL [4] has provided the following definition of resilience: „Resilience is the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions“. To our best knowledge it is the only definition currently known in the context of ATM.

In various domains the terms resilience and robustness have been defined and redefined many times. Even within the same domain there exist different particular meanings. Table I provides a summary of terms found in the literature which are used synonymously.

Table I
Terms with similar meanings

term	robustness	resilience
used in synonymic sense	resilience resistance stability	stability recovery elasticity

Since this paper focuses on the aspects of a performance based approach for investigating resilience of an ATM System that is experiencing disturbances and being provided that safety is given at any time, the definition in [4], derived from the safety science perspective, did not appear sufficient enough for achieving this goal. Because of the simultaneous existence of „engineering resilience“ and „ecological resilience“ and various interpretations of resilience and robustness in different research domains as well, it was necessary to develop a new concept of resilience and robustness with respect to an ATM System. It has to be stressed that a clear differentiation between both terms had to be accomplished, as well as definitions had to be made to enable measurement of the terms. Moreover, in literature, exist many contradictory applications of the terms disturbance, stress and perturbation. So, it was necessary to clarify their particular meaning in the context of ATM. Taking into account the aims mentioned above, one of the authors of this paper has developed a framework in [5], [6], which incorporates a concept of the interdependencies between robustness, resilience and other relevant terms. In this new framework the terms of disturbance, stress and perturbation are linked together to create a new terminology of resilience and robustness in the context of a socio-technical system. There, the term disturbance is defined as a cause, whereas stress and perturbation have been determined as an effect caused by a disturbance. The idea to this logical differentiation of the terms disturbance, stress and perturbation is originated in ecosystems [18].

B. Definition of resilience and robustness in the ATM Context

When deriving an approach to define resilience, the fundamental property of a system, which has to be considered, is the amount of stable states in the system. Both, single and multiple stable states can be observed. Ecological or natural systems show multiple stable states, also named as reference states. In contrast to these systems, an ATM System has only one reference state, which is set up for a specific time horizon by one or more human operators. This reference state can be expressed by single values of performance indicators as well as by intervals or domains where performance indicators can vary. It has to be pointed out, that the specified reference state is not necessarily stable or leads to an equilibrium like in the biological or physical domains. Therefore, the concept of „engineering resilience“, taken as a basis for the definition of resilience in the context of ATM [5], [6], appears as the most suitable. The time or duration a system needs to return to its reference state can be used as the value to measure resilience. In the following, the definitions of the terms in the framework developed in [5], [6] and shown in Fig. 1 are cited:

- **Current state** of a system is defined by the current values of its performance indicators.
- **Reference state** of a system is the specified set of its performance indicators values. A reference state relative to the current state of the system can be either
  - an *actual reference state*, when the current values of the performance indicators are in the specified set of performance indicators values

  or
  - a *potential reference state*, when at least one of the current values of the performance indicators is not in the specified set of performance indicators values.

  A potential reference state may be realistic or nonrealistic with respect to the existing operational conditions.
- **Disturbance** - (a cause) a phenomenon, factor, or process, either internal or external, which may cause a stress in a system; is relative to the specified reference state and considered system; is categorized and quantified by type, frequency, intensity and duration.
- **Stress** - (an effect - a reaction of a system) the state of a system caused by a disturbance which differs from the reference state and is characterized by deviation from this reference condition; can be
  - *survival* - if the system can respond by perturbation without modification to change the current state;
  - *lethal* - if the system cannot or should not respond by perturbation to change the current state and has to be modified.

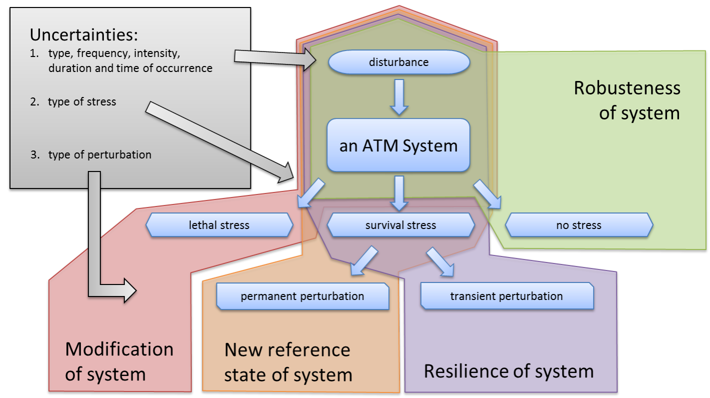

Figure 1. Impact of a disturbance on an ATM System

- **Perturbation** - (an effect - an action of a system) the response of a system to the possible or current significant undesirable changes of the state of the system caused by a disturbance. Perturbation aims at preventing of the changes and/or at minimizing of deviation of the current values from the reference values of performance indicators.

  In the case when stress is unavoidable, but survival, perturbation can be
  - *transient* - if it enables temporary deviation which becomes zero over time with return to the reference state;
  - *permanent* - if deviation becomes fixed over time leading to a state of the system different from the reference state.
- **Robustness** - the ability of a system to experience no stress since a disturbance had occurred, i.e. the system is robust against the disturbance over the considered time horizon; is relative to the specified reference state of the system and to a particular disturbance (see Fig. 1).
- **Resilience** - the ability of a system to respond on a disturbance within a time horizon by transient perturbation, i.e. the system is resilient against the disturbance over the considered time horizon; is relative to the specified reference state of the system and to a particular disturbance (see Fig. 1).

Taken into account the terminology of the framework illustrated in Fig. 1, in case of a disturbance influencing an ATM System, the logical interrelations regarding the state of the system can be explained. The system can react by survival or lethal stress or experience no stress at all. The latter is given when it remains within the boundaries of the reference state for a particular period of time. This system is robust. In the case of survival stress, the system reacts by transient or permanent perturbations, relative to the specified time horizon. Fig. 2 shows an example of stress and perturbation phases of an ATM System. The origins of the coordinate planes in Fig. 2 correspond to the point in time when the reference state of the system is specified. The considered system is resilient against the disturbance, since it reacts with transient perturbation, which enables the temporary deviation from the reference state within the illustrated time horizon.

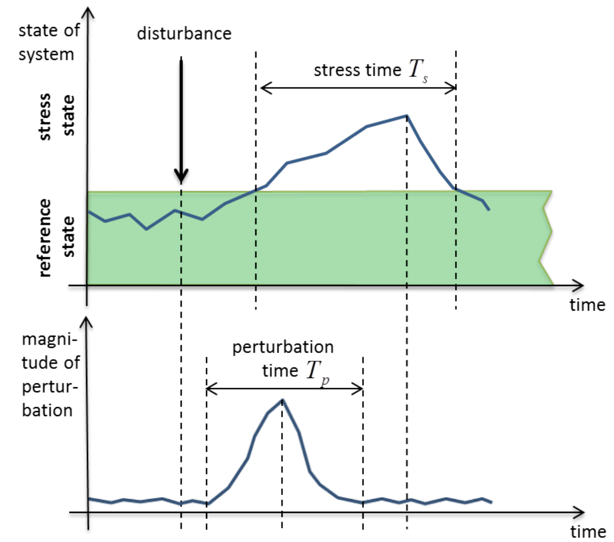

Figure 2. Stress and perturbation phases of an ATM System

As explained above, a robust behavior of a system means, that in case of an occurring disturbance its state remains within the boundaries of the specified reference state, which in general is given as a domain. In contrast to that, resilient behavior means that the state of the system crosses the boundaries of this domain for a particular period of time. Since resilience and robustness are depending on a defined reference state, a time horizon as well as a particular disturbance and are determined by the means of performance indicators, both properties can be investigated in the same manner. Regarding the performance based approach, which is proposed in this paper, the authors will address hereafter both, resilience and robustness.

Sources of uncertainties in the ATM Context, that are not reliable or are unknown, can be divided into four major groups: human, transparency of data, meteorology and equipment [8]. It is uncertain, which type, frequency, intensity and duration a disturbance will possess at the moment of its occurrence (see Fig. 1). Depending on the particular ATM System, which is influenced by a disturbance, it is uncertain in which way the system will react on the disturbance and how the system will act to minimize the deviation from its reference state.

III. Proposition how to measure resilience and robustness

Resilience and robustness of a system cannot be investigated and improved if they cannot be measured.

Since an ATM System is a socio-technical system and to illustrate the interrelations described in Fig. 1 with regard to the perspective of a stakeholder, the functional structure of the framework demonstrated in Fig. 1 was transferred to the corresponding decision-making chain shown in Fig. 3. The colors of the arrows in Fig. 3 correspond to the according blocks in Fig. 1. The particular steps in the decision-making chain can be reproduced by following the framework proposed in Fig. 1. The rungs of the decision-making chain, in which resilience and robustness of an ATM System can be measured, are illustrated in Fig. 3.

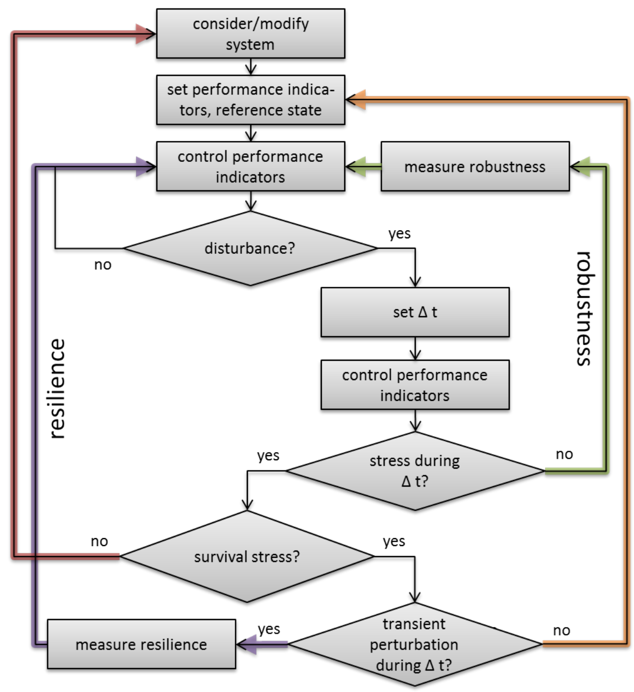

Figure 3. Decision-making chain according to Fig. 1

As a qualitative measure of resilience we propose the comparison of time of deviation T_d with time of recovery T_r, illustrated in Fig. 4-6. The time of deviation with respect to its reference state is the duration, whilst the state of a system accumulates its maximal difference, taken on from the moment when the system abandons this state. Time of recovery is the duration a system needs to return from the maximal deviation state to the reference state. Hence, one can distinguish among:

- *high resilience* - time of deviation is considerably longer than time of recovery: $T_d >> T_r$ (Fig. 4);
- *medium resilience* - time of deviation and time of recovery are approximately equivalent: $T_d \approx T_r$ (Fig. 5);
- *low resilience* - time of deviation is considerably shorter than time of recovery: $T_d << T_r$ (Fig. 6).

The idea of this concept of measuring is originated in material testing [9]. Quantitative resilience can be measured as

- degree of recovery in a specified time [9];
- the overall time a system needs to return back to the reference state by transient perturbation.

As quantitative measures of robustness can be

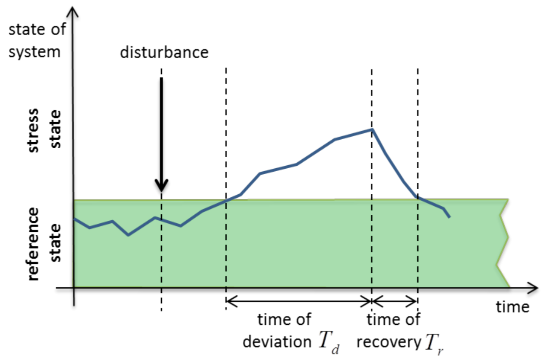

Figure 4. High resilience of an ATM System against a disturbance

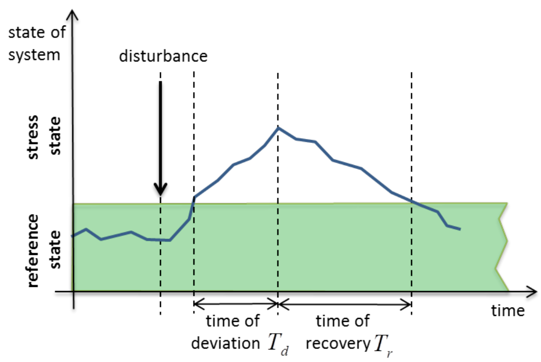

Figure 5. Medium resilience of an ATM System against a disturbance

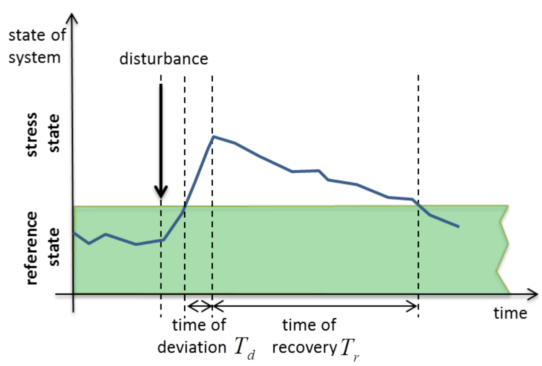

Figure 6. Low resilience of an ATM System against a disturbance

- the maximal „amount“ of a disturbance quantified by frequency, intensity and duration, which can be absorbed by a system, i.e. the system experiences no stress;
- the minimal distance to the limits of robustness, where a system still not experiences stress, for a particular disturbance of some frequency, intensity and duration.

Another qualitative and quantitative measure of resilience or robustness can be cost related when increasing resilience or robustness of a system. For instance, time buffers or expansion of the system with regards to integration of other transportation systems or the extension of resources could be introduced. All these procedures are inducing further costs. Other methods to measure resilience and robustness, different to the ones described above, could be defined according to the goals of stakeholders involved in the process.

IV. Performance based approach

A. Modeling approach of an ATM System

In order to investigate resilience and robustness of an ATM System and to identify ways of improvement, a modeling approach has to be formulated that on the one hand considers all relevant features of the system, but on the other hand, due to the fact that it is a first approach applying the new concept of resilience and robustness, it has to be realizable. Resilience and robustness, as stated in Chapter II, are generally valid for socio-technical systems and formulated depending on changes of performance indicators after the occurrence of disturbances. The aim is to apply resilience and robustness on the socio-technical ATM System. Regarding the increasing importance of collaborative decision making processes in the future ATM System, as proposed by SESAR [19], the accordant modeling approach aims to emphasize the sociological dimension of the system. The goal is to draw conclusions how to improve the system in the range of decision making processes, making the system more robust or resilient against a particular disturbance.

In this paper, an ATM System, which among other things inherits the following properties

- complex structures of components in space and time scales;
- organization of patterns and processes by human with help of supporting tools;
- dynamic, but insufficient flows of data and information;
- hierarchical structure;
- stochastic influences on system,

will be divided into two dimensions. On the one hand, the stakeholders with the according systems and tools, subsequently denoted as Dim_1, on the other hand, the physical movement of the aircraft - Dim_2. The division into two parts is adopted from the modeling architecture of widely spread simulation tools like Simmod PRO! or AirTOp. As shown in Fig. 7, the motion of the aircraft within the airspace can be abstracted as a result of decisions made by particular stakeholders in Dim_1. The aircraft, in Dim_2, is guided by a pilot, executing the decisions and being the central element combining both dimensions of the system. The motion of the aircraft not only depends on the decisions made in Dim_1, but also on its particular performance characteristics. The resulting movement of the aircraft in Dim_2 causes a reaction in Dim_1, which itself again induces a decision-making process.

To investigate resilience and robustness, as defined in Chapter II, a hierarchical structure of a selection of involved stakeholders was implemented in this modeling approach. The structure is adopted from the work in [2] and represents the segmentation of the inherent stakeholder hierarchy. Superior to this structure, socio-economical expectations of the society are formulated. The main stakeholders are resolved in a division level and an individual level successively. For reasons of clarity Fig. 7 shows a selection of elements of the ATM System. The various levels of the hierarchical sociological structure in Dim_1 are interconnected. When necessary, one can keep track of a decision

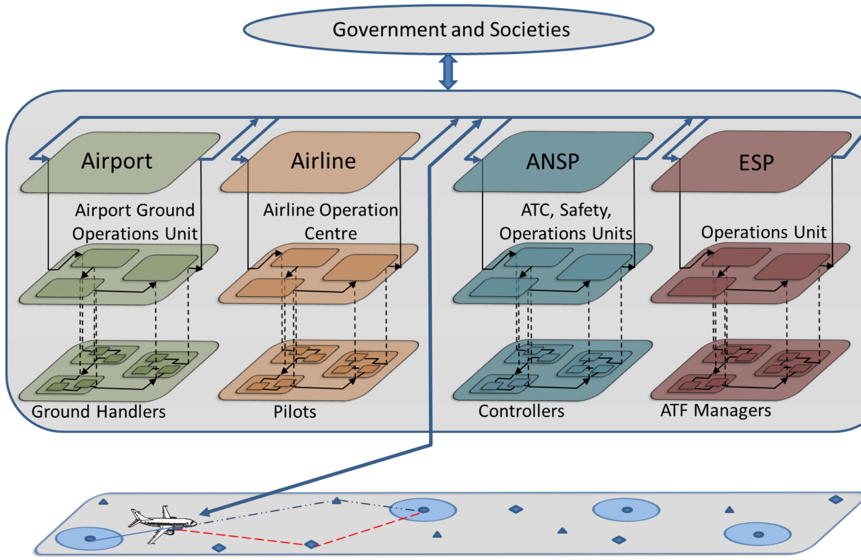

Figure 7. Socio-technical view on an ATM System

made at a particular level by following the according lower level, revealing the interrelations in more detail. A simple example serves to illustrate the principle of the modeling approach. An aircraft delayed because of resource shortages during the turnaround process at the airport will receive a new slot by the air traffic flow manager. Ground- and runway controller are guiding the pilot till the ATC takes over. Because of weather disturbances, a sector controller might chose a trajectory different to the one originally planned (the red respectively blue dotted line in Fig. 7). Any decisions occurring during this flight leg should be traceable in the hierarchical structure.

B. *Algorithm to investigate resilience and robustness*

Since resilience and robustness, like proposed in this paper are properties of a system, there is a set of steps that are essential to perform for their investigation.

The *first step* of the proposed algorithm is to define and describe the system, one would like to investigate, and its boundaries to the environment. Considering the spatial expansion like shown in Fig. 7, a number of airports will be selected. The selected airports are elements of Dim_1, but are also reflected in the geographical representation in Dim_2. Considering other involved stakeholders, a selection has to be made as well. Because of the different effects anticipated at the various levels of the hierarchical structure, when investigating implications of disturbances respectively analyzing the reaction of the resilient or robust system, it is necessary to specify the level of hierarchy at which the system will be observed. This builds the *second step* of the algorithm. Due to the fact that this paper proposes a performance based approach, which reflects in a definition of resilience and robustness depending on the state of the system, performance indicators describing the state of the system have to be selected in *step 3*. When the performance indicators are declared, the reference state will be specified in the *following step*. Now we are prepared to indicate respectively to select disturbances, i.e., as defined in Chapter II, phenomena, factors or processes, either internal or external, which may cause stress in the considered system. This will be done in the *fifth step*, where it is now possible to classify disturbances by type, frequency, intensity and duration. However, we should always keep in mind that the scale, at which the system is observed, is a most important factor determining the level of detail required in characterizing disturbances and their impact on the system. Since resilience and robustness are time dependent, it necessary to set up a time horizon, within both properties will be explored. To investigate resilience and robustness the following six steps summarized in Algorithm 1 have to be performed.

Algorithm 1 Investigation of resilience or robustness of a system

1: Define and describe the system and its boundary to the environment;
2: Specify the scale and/or the level of hierarchy to observe;
3: Define the performance indicators describing a state of the system;
4: Specify the reference state of the system;
5: Indicate and classify disturbances by type, frequency, intensity and duration;
6: Set the time horizon and investigate resilience or robustness of the system.

With the help of this modeling approach, the implications of disturbances on the specified ATM System can be evaluated by means of performance indicators. Weak points in the procedures of the particular stakeholder shall be revealed. Provided that in future, a system wide information management [19] is implemented and a commitment of the different participators to act collaboratively exists, the hierarchical structure should enable to draw conclusions how collaborative operations can be optimized. In the context of improving collaborative decision making processes, the modeling approach may reveal occurring problems at the particular level of a stakeholder system in

Dim_1. For instance, a thunderstorm causing heavy workload in a specific sector could be mitigated by a different operation procedure like proposed in the sectorless ATM Concept [1]. In Fig. 7 this could affect the ANSP stakeholder at the second level. When investigating the system, besides the change of operational procedures, adaption of resources can diminish the effects of a disturbance. In our example with the delayed aircraft, a ground handler could be assigned with additional staff. That reflects in the third level of the airport stakeholder system.

Besides new conceptual rules of operations or an according adaption of resources, this modeling approach enables to point out different solutions to achieve the same performance targets. For example, the integration of ground transportation systems like the railway can be investigated in order to analyze its potential to improve the performance of the whole system. In the hierarchical structure presented in Fig. 7 this corresponds to the addition of new stakeholder system.

Summarizing the points above, in order to obtain a more robust or more resilient system against a particular disturbance one has to:

- investigate the system;
- adapt resources, processes and the behavior of the system accordingly;
- find potential alternative ways that lead to the same goal, which are as independent as possible.

This three-step approach aims to enable a faster returning of the system to its reference state. It can be done by understanding the functionality of processes and reactions of the system and by applying the obtained knowledge.

V. Conclusions

In this conceptual paper a new methodology to help realizing the implementation of performance targets set by SESAR by means of increasing the resilience or robustness of the ATM System was developed. The presented methodology included an extended definition of resilience regarding its safety dimension. In this context a clear differentiation between resilience and robustness was established. The universal character of the terminology allows a general application on socio-technical systems on different scales. Furthermore, a proposition how to measure resilience and robustness was presented. In order to apply the principles derived in the methodology and to investigate the impacts of disturbances, a modeling approach, which focuses on the abstraction of the system in the form of stakeholders on the one and the movement of the aircraft on the other hand was introduced. In this context an algorithm that summarizes necessary steps, that have to be performed in order to investigate resilience and robustness, was developed.

In the following work, the particular system to be investigated will be described and subsequently be modeled in the way presented in the paper.

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Author Biography

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Peter Förster works as a researcher at the Institute of Flight Guidance of the German Aerospace Center at Braunschweig. His fields of study are discrete event simulation in the context of ATM and trajectory calculation. He joined DLR at 2006 after finishing his Diploma in Aerospace Engineering at Technical University Berlin. Peter Förster is currently pursuing his Ph.D in Aerospace Engineering.