Definitions of Disturbance, Resilience and Robustness in ATM Context*

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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, one of which is an ATM System. In ecology and in other domains there are a lot of definitions and interpretations of the term resilience. Most of them fall into two big groups with semantical meanings „resilience“ and „robustness“. Currently in the ATM Context exists a definition of resilience from the safety science perspective only. Since we investigate resilience of an ATM System from the more general - performance point of view, which includes safety with performance aspects, it is necessary to develop conceptual definitions of resilience and robustness of an ATM System, which have a clear differentiation between these terms and enable their measurement.

The aim of this report is to give a short description of the developed framework, which incorporates created concept of robustness, resilience and relevant terms: disturbance, stress and perturbation. The developed framework is illustrated with one simple example and is accomplished with an according decision-making chain. The report also suggests some qualitative and quantitative measures of resilience and robustness and provides a structured approach for investigation of these properties of a system. In spite of the fact, that the concept is developed in the ATM Context, it is transferable and can be used for any socio-technical system.

Keywords: resilience, robustness, disturbance, stress, perturbation, ATM System

1 Introduction

The term resilience was first introduced by Hoffman [6] in 1948 in the field of mechanics and material testing. Holling [7] has proposed one decade later the term in ecology. Currently the concept of resilience is one of the most interesting and important research

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topics. Up to the present time several thousand papers and books have been published on resilience in different research domains. In ecology there are, for instance, two definitions of resilience, which exist in parallel. There resilience is considered either

1. as „the time required for a system to return to an equilibrium or steady-state following a perturbation“ [11], [5] - this definition of resilience has been termed as „engineering resilience“ by Holling [8], [5]

   or

2. as „the ability of a system to absorb changes of state variables, driving variables, and parameters, and still persist“ [7] or as „the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks“ [14] - has been named „ecological resilience“ [8], [5].

The first definition assumes the persistence of single or global equilibrium or stable state while the second sets multiple equilibrium/stable states.

Oxford Dictionary [10] 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, „engineering resilience“ tends semantically to resilience and „ecological resilience“ inclines to robustness. A well structured overview on robustness or „ecological resilience“ the reader can find in [1]. The terms resilience, robustness have been defined and redefined many times with different meanings in other domains. Table 1 provides a summary of terms used in the synonymic sense we have found in the literature.

Along with the term „engineering resilience“ Hollnagel et al. [9] have introduced in 2006 the concept of „resilience engineering“ in safety science, which investigates human and organizational aspects in the design of safety critical socio-technical systems. „Resilience

Table 1: Terms with similar meanings

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

engineering is a paradigm for safety management that focuses on how to help people cope with complexity under pressure to achieve success“ [9]. 2007 EUROCONTROL has launched a project „with the aim of understanding the new area of Resilience Engineering and its relevance to Air Traffic Management“ [3] from the safety science perspective. In the White Paper on Resilience Engineering for ATM EUROCONTROL has provided in 2009 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“ [3]. It is the only definition we have found in the ATM Context. Since we are concentrated on resilience of the performance of an ATM System, which includes safety with other performance aspects, the definition from a safety science perspective is not sufficient enough for this purpose. Because of the simultaneous existence of „engineering resilience“ and „ecological resilience“ and various interpretations of resilience and robustness in different research domains, it is necessary to develop conceptual definitions of resilience and robustness of an ATM System, which have a clear differentiation between these terms and enable their measurement. We define them according to the semantic meanings [10].

Since the properties of resilience and robustness of a system are only visible in the case of occurring disturbances, we need first a general definition of disturbance in the ATM Context. We have not found such a definition, but have discovered a very interesting paper about ecological disturbance created by Rykiel [13], which illustrates a structured approach to define the terminology. The author of the paper considers disturbance as a cause, while stress and perturbation as an effect triggered by the disturbance. We use this logical background and two types of stress and perturbation in ecology in order to define disturbance, stress and perturbation in the ATM Context.

In spite of the fact, that the concept is developed in the ATM Context, it is transferable and can be used for any socio-technical system.

2 Concept of resilience and robustness of an (ATM) System

2.1 Definitions

In the general system theory the number of definitions of a system multiplies constantly - „every second author proposes a new definition“[4]. We consider the following definition of a system [2]:

Definition 1. ***System*** *is a framework of objects and relations with particular attributes.*

An ATM System (the whole ATM system or any of its subsystems, for instance, a planning system, an airport etc.) can be characterized by:

- Specific purpose;
- 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;
- Change in system structure, organization and components over time („evolution“);
- Non-linearity in patterns and processes;
- Scale in which system is defined and observed;
- Hierarchical structure;
- Stochastic influences on system.

Hence, an ATM System is a complex hierarchical socio-technical system influenced by external and internal disturbances.

In order to evaluate the work of a system, primarily performance indicators describing a state of the system and its reference state have to be specified.

Definition 2. ***Current state*** *of a system is defined by the current values of its performance indicators.*

Definition 3. ***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

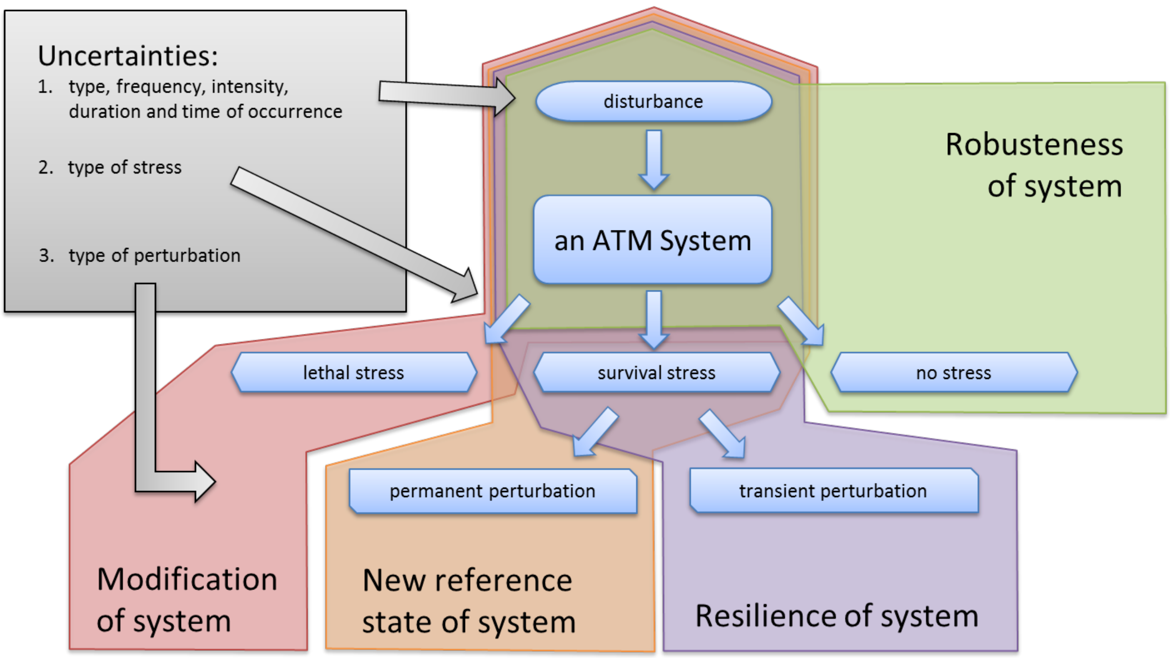
- *a potential reference state, when at least one of the current values of the performance indicators is not in the specified set of performance indicators values.*

A potential reference state may be realistic or nonrealistic with respect to the existing operational conditions.

A reference state can be established by single values of performance indicators as well as by intervals or domains where performance indicators can vary.

Since resilience and robustness of a system depend on disturbances, it is necessary to define disturbance in ATM Context. Disturbance is considered as a cause of possible effects, namely stress and perturbation, in a system.

Figure 1: *Impact of disturbance on an ATM System*



Definition 4. ***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.*

It is important to note (see [13]), that

- the scale in which a system is defined and observed is a most important factor determining the level of detail required in characterizing disturbances and their impact on the system;

- in a hierarchically structured system, a disturbance at any level can be „absorbed“ by moving up the hierarchy.

Therefore, the scale in which a system is considered and the level of hierarchy in it determine the relevance of a disturbance and the level of detail in its characterization.

A system can be influenced by a disturbance and, therefore, can be stressed.

Definition 5. ***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.*

Definition 6. ***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.*

So a system, which is influenced by a disturbance, can react by stress and in the case of survival stress act by transient or permanent perturbation. This framework enables us to define robustness and resilience of a system. Robustness is described as the ability of a system to absorb a disturbance while resilience is given as the ability of a system to return back within a specified time horizon since a disturbance had occurred.

Definition 7. ***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 Figure 1).*

Definition 8. ***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 Figure 1).*

Both introduced terms - robustness and resilience of a system - are time dependent, i.e. evaluated within a given or defined time interval. The action of a system remaining in the framework (see Figure 1) - permanent perturbation - leads to a new reference state of the system and the remained reaction of a system - lethal stress - causes its modification.

The developed concept has clear differentiation between the terms robustness and resilience. A grade of an influence of a disturbance on a system is illustrated in Figure 1 schematically by a color and by a depth of the colored blocks: from the green area, where the system is not influenced, down to the red one, where it has to be modified.

2.2 An example and decision-making chain

Let us consider an airport A as an ATM System, a throughput of its runway system as a performance indicator, the throughput

$$TP = \min\{\text{from } n_1 \text{ up to } n_2 \text{ flights per hour; demand per hour}\}, \text{ where } 0 < n_1 \leq n_2$$

as a reference state and a winter season as a disturbance.

When over the period of the winter season the airport A holds the reference state, i.e. has the throughput TP, it has no stress and is robust against this disturbance (see Figure 1). However, this situation is possible in airports working under its nominal capacity only. More realistic is the condition where the throughput become smaller, for instance

$$TP^w = \min\{\text{from } n_1^w \text{ up to } n_2^w \text{ flights per hour; demand per hour}\},$$

$$\text{where } 0 < n_1^w \leq n_2^w < n_1 \leq n_2.$$

Hence, the considered system - airport A - is under stress.

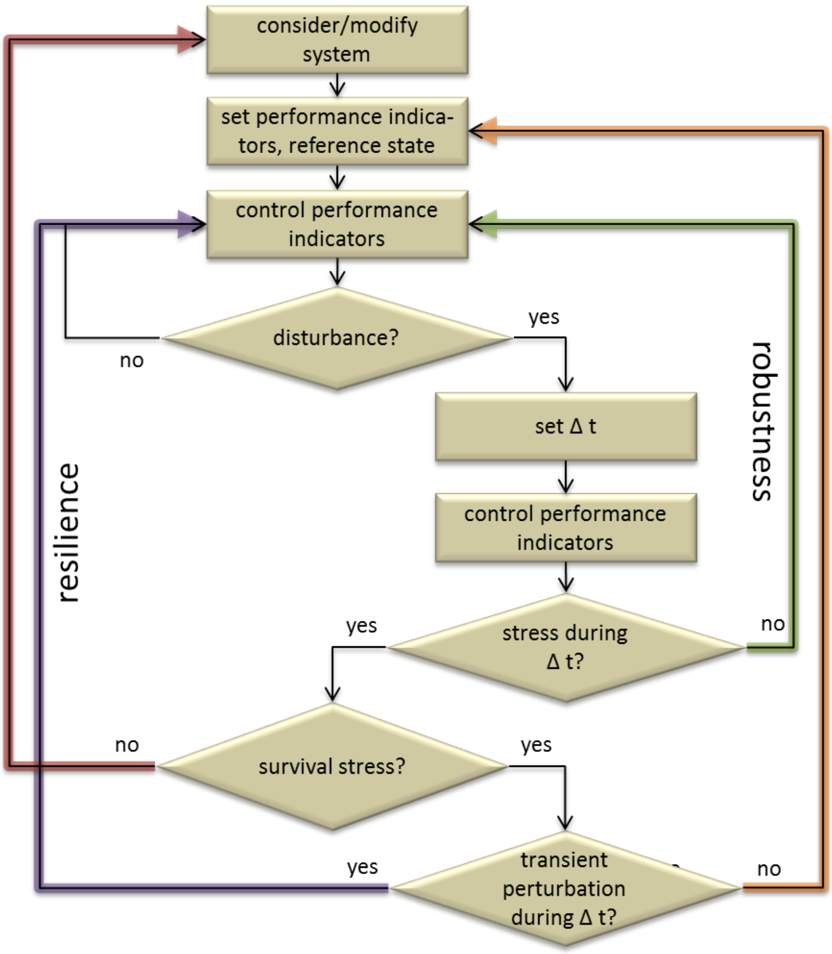
When the stress is survival and the considered time horizon is the length of the winter season, the airport A is resilient against the winter season, since it reacts by transient perturbation and returns back to the reference state TP at the end of the season (see Figure 1). However, if the time horizon is considerably shorter than the length of the winter season and the system is under survival stress, this means it acts by permanent perturbation because of the throughput TP^w. Therefore, it makes sense to set the throughput TP^w as a new reference state (see Figure 1). Otherwise, if it is decided the airport A is under lethal stress, i.e. the throughput TP^w cannot be accepted, the airport has to be modified (see Figure 1). For instance, its demand can be reorganized so that some flights can be replaced by train or the relevant airport equipment can be adjusted.

It is only a simple example illustrating the framework in Figure 1. One corresponding to the framework decision-making chain is shown in Figure 2, where the colors of arrows are similar to analogous blocks in Figure 1.

2.3 Importance of reference state

As it is already indicated by Definitions 7 and 8, robustness and resilience of a system depend on its specified reference state. An actual reference state enables all five reactions

Figure 2: *Decision-making chain according to Figure 1*



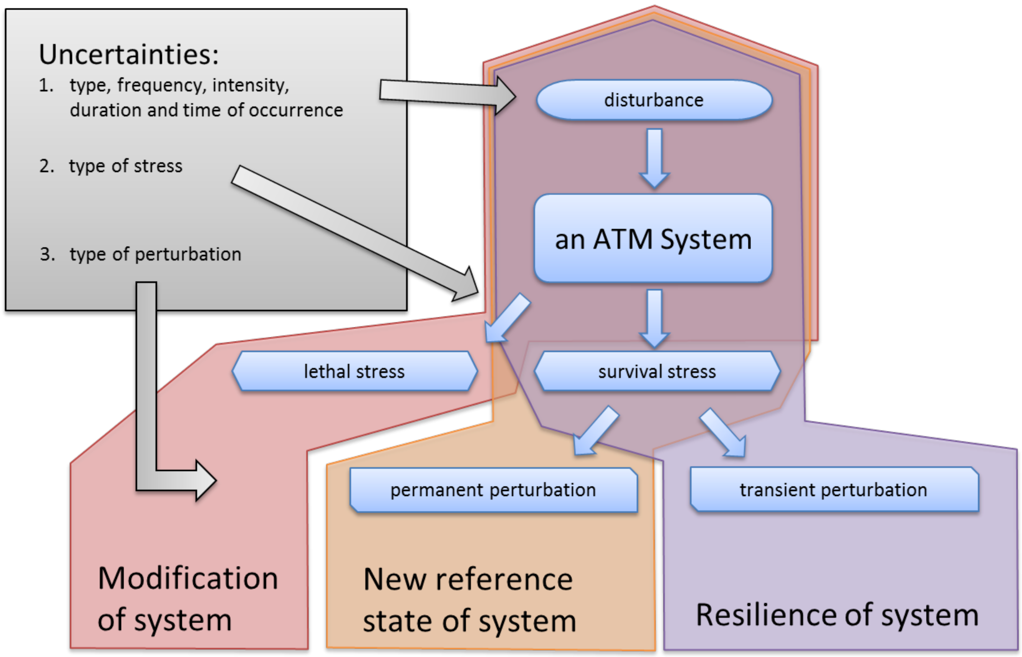
and actions of the system on a disturbance, which are summarized in Figure 1. Hence, the system can be robust or resilient against the considered disturbance.

However, if the system has a realistic potential reference state it cannot be robust against a disturbance, since the current state of the system differs from its reference state, i.e. the system is under stress (see Figure 3).

A nonrealistic potential reference state influences the system so that it cannot be robust or resilient against a disturbance, because it is under stress and cannot return back to this reference state (see Figure 4).

The specification of a potential reference state, realistic or not, should be considered as a disturbance factor for the system. This disturbance causes stress at any case and the system cannot be robust against such disturbance. However, it can be resilient against a realistic potential reference state. A nonrealistic potential reference state leads either to lethal stress or to survival stress with permanent perturbation and, as a consequence,

Figure 3: *Impact of realistic potential reference state*



either to modification of the system or to a new reference state.

2.4 Some ways to measure resilience and robustness

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

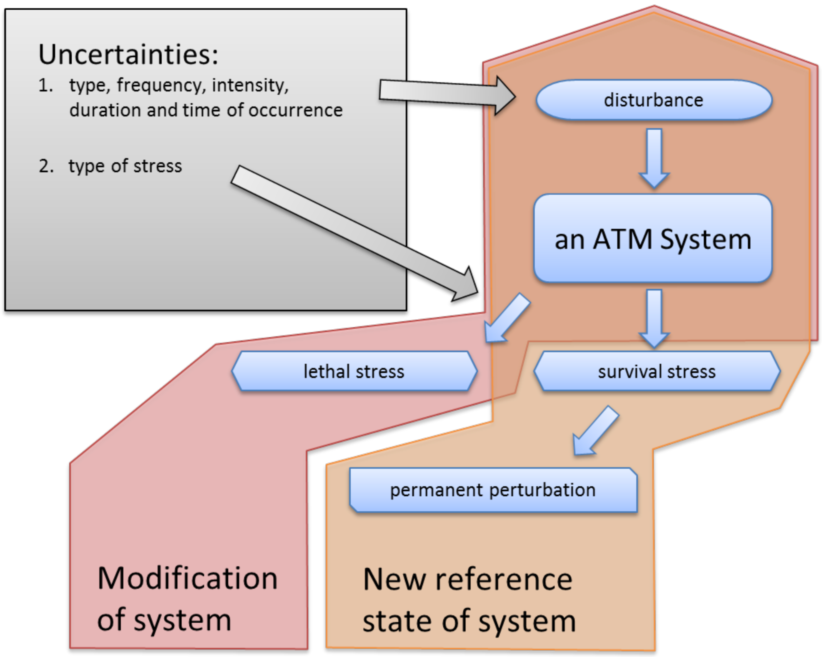
As a qualitative measure of resilience we propose the comparison of time of deviation with time of recovery. Time of deviation is the duration the state of a system obtains the maximal difference to the reference state from the moment when the system leaves this state while time of recovery is the duration 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;
- medium resilience - time of deviation and time of recovery are approximately equivalent;
- low resilience - time of deviation is considerably shorter than time of recovery.

The idea of this measure is originated in material testing [6]. Quantitative resilience can be measured as

- degree of recovery in a specified time [6];

Figure 4: *Impact of nonrealistic potential reference state*



- the overall time a system needs to come back to the reference state by transient perturbation.

As quantitative measure of robustness can be

- the maximal „amount" of a disturbance quantified by frequency, intensity and duration, which can be absorbed by a system, i.e. the system has no stress;
- the minimal distance to the limits of robustness, where a system still has no stress, for a particular disturbance of some frequency, intensity and duration.

Another qualitative and quantitative measure of resilience or robustness can be costs induced by recovery or by robustification of a system (for instance, buffers or expansion of a system), respectively. However, other different from mentioned above types of measures can be defined according to goals of stakeholders involved into the process.

2.5 Structured approach for investigation of resilience and robustness

Summarizing Sections 2.1-2.3 the following steps are crucial for investigation of resilience and robustness of a system:

1. Define and describe the system and its boundary to the environment;

2. Specify the scale and the level of hierarchy to observe;
3. Specify performance indicators describing a state of the system;
4. Specify reference state of the system;
5. Classify disturbances by type, frequency, intensity and duration keeping in mind that the scale in which the system is defined and observed is a most important factor determining the level of detail required in characterizing disturbances and their impact on the system.

Only thereafter one can proceed with studying of the impact that the relevant to the system disturbances cause.

Resilience is a property of adaptive systems [12]. Hence, in order to obtain a 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 approach aims a faster return of the system to its reference state by learning of the processes and reactions of the system and by application of obtained knowledge.

3 Summary

This report gives a short description of the framework created by determining of robustness, resilience and relevant terms: disturbance, stress and perturbation in ATM Context. The developed conceptual definitions, which determine resilience and robustness of an ATM System from the performance point of view including safety with performance aspects, offer clear differentiation between these terms and enable their measurement. The created framework is illustrated with one simple example and is accompanied with an according decision-making chain. Additionally, the report suggests some qualitative and quantitative measures of resilience and robustness. The constructed framework enables structured approach for investigation of these properties of an ATM System with respect to the relevant disturbances and their impact on the selected system.

Although the concept is created in the ATM Context, it is transferable and can be used for any socio-technical system.

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