New Reliability Prediction Methodology Aimed at Space Applications

TN-05 Fact Sheet on the

Development of the new reliability prediction methodology for space applications

Under a programme of and funded by the European Space Agency

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Executive Summary
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TN-5 Executive summary

The Technical Note TN-5 provides the findings and major results of the Task 5 prepared in the frame of the study “New Reliability Prediction Methodology Aimed at Space Applications”, under a programme of and funded by the European Space Agency.

The objective of the study is the development of a new methodology for reliability prediction (RP) for space applications, aiming to overcome the limitations and shortcomings of the methods and approaches currently used in practice. The final outcome of the study will be a handbook for reliability prediction in space applications, which will serve as an input for the development of a new ECSS handbook. The role of the Technical Note TN-5 for the overall study is shown in Figure 1 below.

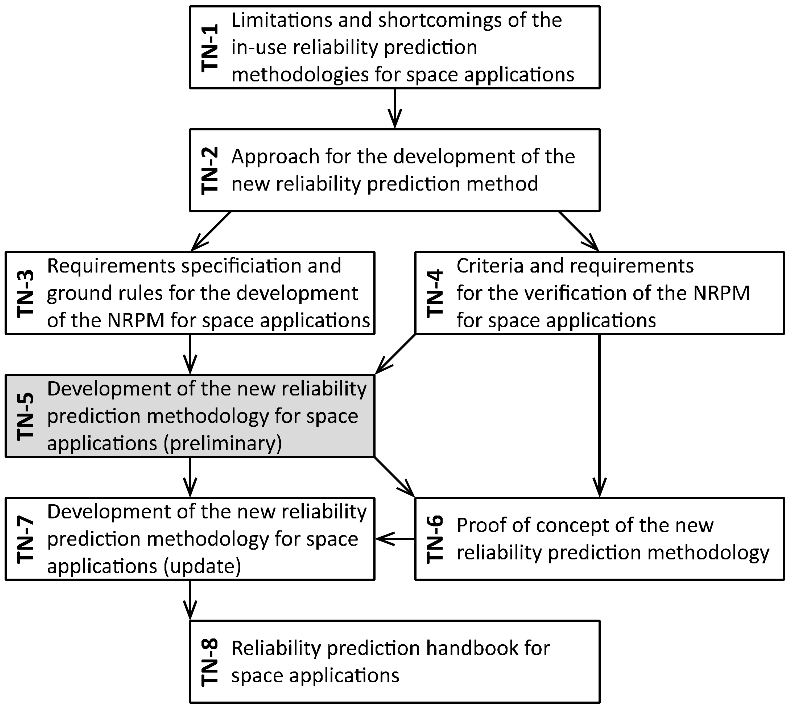

Figure 1: Overview on the content and interrelation of the Technical Notes.

Before the end of Task 5, a workshop was held at ESTEC with relevant stakeholders from the space industry. The workshop objectives were the following:

- to share the status and progress of the study and give an overview on the ongoing work
- to discuss choices made during the development and underlying assumptions
- to get feedback at an intermediate step during the progress of the study

The discussions during the workshop showed that the development of the new reliability prediction methodology was progressing well and was generally going in the right direction. The detailed discussions and comments were considered during the finalization of Task 5

The objective of TN-5 is the development of a new reliability prediction methodology for space applications. It is based on the approach defined in TN-2 (see TN-2 Fact Sheet for a short summary) and the requirement specificiations and ground rules defined in TN-3 (see also TN-3/4 Fact Sheet). It serves as a basis for the proof of concept in TN-6 and – after performing an update in TN-7 – will be used as the major input for the final reliability prediction handbook (TN-8).

TN-5 already follows the structure of the final handbook, which will be divided in three volumes and a preface. Each volume has its intended audience, focussing on a specific use of the reliability prediction handbook, see Figure 2 for details. The average handbook user whose task is to perform a prediction with the given models will find all required material in Part III. It is, however, assumed that the user is familiar with the basic notions and concepts introduced in the other parts, e.g. the taxonomy explained in Part I.

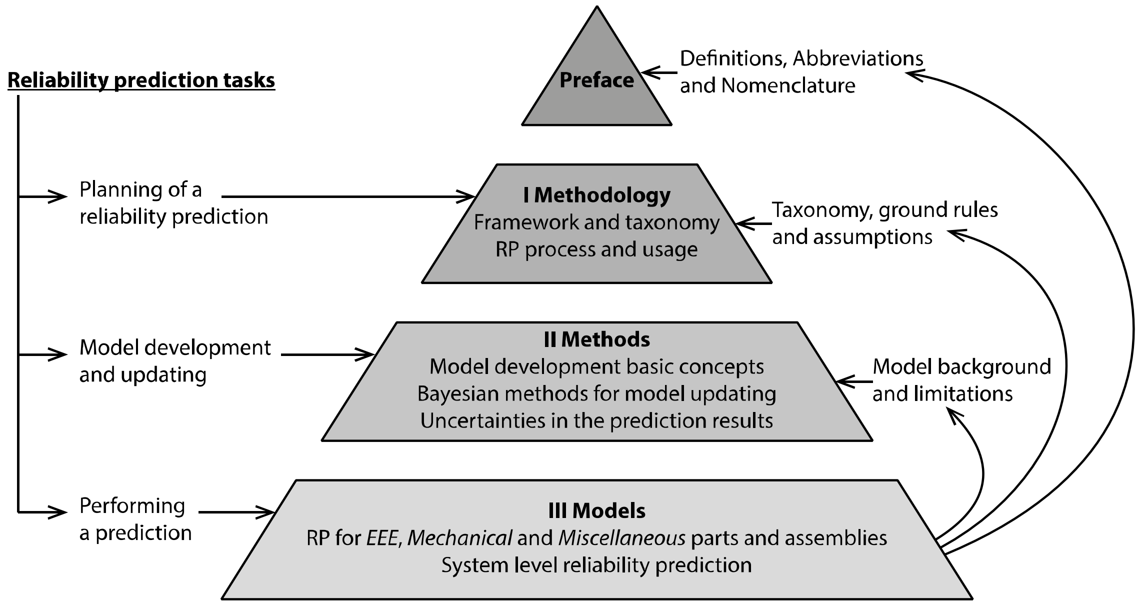

Figure 2: Overview on the three handbook volumes and their usage by reliability prediction task.

In the following, the content and development of each part is briefly outlined.

Part I – Methodology

This part of the TN explains the framework and taxonomy used in the handbook and links it to the reliability prediction process and usage. It provides guidance for handbook users that are in charge of planning a prediction.

The taxonomy is defined on two major axes, addressing

- The type of elements: EEE, Mechanical and Miscellaneous elements, each covered by a dedicated chapter in Part III. System level considerations are independent of this classification.
- The failure root causes: Random, systematic, wear-out and extrinsic failures are distinguished according to TN-1 classification (see also TN-1 Fact Sheet).

To achieve reliability predictions that are clear, specific and useful, the methodology framework defines a number of ground rules and assumptions that must be agreed before starting with a prediction. A key concept is the intended use of the prediction (see TN-2 Fact Sheet), which determines the required scope and focus in terms of failure root causes to be covered. Providing input to the design is the classical use of reliability predictions, requiring full coverage of random failures plus additional consideration of other root causes for specific trade-offs or technologies (e.g. those prone to premature wear-out). As an input for business planning, which is another reliability prediction use, the scope may be extended to cover also systematic failures due to their large contribution to the overall failure count. An appropriate consideration of wear-out failures is required to support decisions about satellite life time extensions versus safe disposal. Part I also discusses how these different reliability prediction tasks and uses are linked to the phases of a typical space project.

Part II – Methods

This part of the TN provides information on different modelling inputs and reliability prediction methods, allowing to understand the background and limitations of the models defined in Part III, as well as to update existing models with new data and to develop new models in consistency with the handbook philosophy.

Different reliability prediction inputs are used with the following preference ordering:

1. *In Orbit Return data* – information on observed failures and cumulated hours collected by operators, prime contractors and manufacturers at different levels
2. *Manufacturer data* – general data used to describe the item under analysis as well as reliability data compiled from In Orbit Return, on-ground testing or other sources that are consistent with the recommendations made in Part III.
3. *Test data* – data from tests performed on ground, such as e.g. reliability or lifetime tests

4. *Handbook data* – models and data from existing reliability handbooks, when consistent with the recommendations made in Part III. In the special case of mechanical reliability prediction, this input has the lowest preference, failure mechanism analysis generally being preferred.
5. *Failure mechanism analysis* – identification and modelling of the relevant failure mechanisms of the considered item

Based on these inputs, reliability prediction models can be derived using statistical methods, Physics of Failure approaches or a combination of both. An overview on the different methods is given in Figure 3, highlighting which kind of inputs is used by which method. For each class of methods, an overview is given, providing guidance on the modelling process and the available methods as well as their strength and limitations. Specific attention is given to the combined approach using methods from Bayesian statistics, allowing to make best use of all available information.

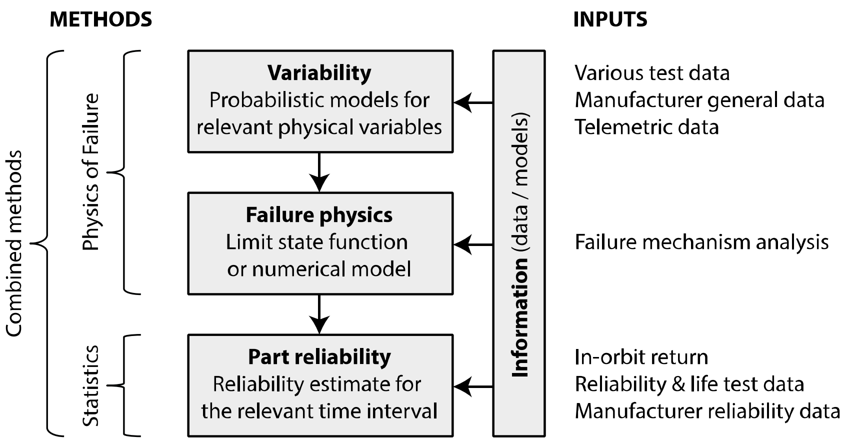

Figure 3: Relation between different types of reliability prediction methods and the available inputs.

Finally, a discussion of uncertainties associated with a reliability prediction is provided, including model development uncertainties as well as model usage uncertainties. A thorough discussion of statistical uncertainties associated with part level models (usually expressed with the aid of confidence bounds for statistical estimates) showed that their impact diminishes at system level due to statistical independence of different elementary models. It is therefore recommended to take a more general view on model development uncertainties, including also aspects such as e.g. data representativeness and different modelling assumptions. A standardized approach to assess various prediction uncertainties is proposed, making use of simple questionnaires. The aim is to identify and clearly communicate the most relevant uncertainties associated with a prediction. An assessment of the models presented in Part III is provided in a dedicated annex, allowing to get a quick overview on their uncertainties and limitations.

Part III – Models

This part of the TN defines the models and data to be used for reliability prediction in space applications. It contains three chapters for elementary reliability modelling of EEE, mechanical and miscellaneous items, and one for reliability prediction at system level. Each chapter is briefly discussed in the following.

EEE components and assemblies

For the modelling of EEE components, the FIDES methodology was used as a basis. To improve its applicability in space, it has been customized as follows:

- Description of the methodology and process to be followed for the definition of a mission profile considering the environmental and use conditions in space applications, with example mission profiles provided for GEO and LEO missions.
- Recommendations for the modelling of different component families and technologies listed in the European Preferred Parts List (EPPL). This includes:
  - recommendations for technologies not covered by FIDES
  - recommendations for innovative technologies and FIDES model updates based on an ongoing study led by the French Ministry of Defence (PISTIS study)
- Space customization of quality related factors, accounting for the specific manufacturer and component quality assurance processes followed in the space industry.
- Space customization and simplification of factors related to the component's placement and usage, considering the specific aspects of space missions.
- Adaptation and simplification of the audit used to derive the process factor with suggested answers for each audit question based on the typical processes followed in space.

In addition to this space customization of FIDES, a dedicated discussion of systematic, wear-out and extrinsic failures shows how these root causes can be covered, if needed, depending on the use of the reliability prediction.

Mechanical parts and assemblies

The approach for Mechanical items takes basis in a previous ESA study investigating the use of different inputs and methods for the assessment of mechanical reliability. The credibility and space applicability of existing mechanical reliability data sources is low, which is why a strong effort was put into the identification and modelling of relevant failure mechanisms and their probabilistic representation in a Physics of Failure based reliability prediction approach. To limit the efforts required for the assessment of mechanical items based on these methods, a process was defined starting with the identification of the dominating failure mechanisms (to support the decision *what* should be modelled), for which then suitable methods are selected to make best use of the available data and engineering knowledge (i.e. providing guidance on *how* the dominating failure mechanism should be modelled).

The use of structural reliability methods beyond the pure structural domain is the core of the methods proposed for mechanical domain. Limit state functions and simplified analytic models are proposed for several failure mechanism, including different types of mechanical wear, fracture/fatigue, and radiation degradation. These models can be applied to any item or technology for which the considered failure mechanism is of relevance, making use of design information enhanced by a probabilistic modelling of the uncertainties associated with the different input variables.

Finally, an approach for Bayesian updating with test data or in-orbit return has been developed, allowing to combine a prior model based on the Physics of Failure with observations. This combination of different inputs is highly effective to improve the prediction with the aid of new or existing data, even if the sample size of the data is too small for a pure statistical analysis.

Miscellaneous items

The category of Miscellaneous items includes mainly parts and assemblies that are difficult to classify into one of the two previous categories, but also items that are either EEE or Mechanical by nature but difficult to model with the domain specific methods. The process proposed for reliability prediction of these items is a step-wise procedure starting with the selection of an initial model (e.g. base failure rate or probability of failure for one-shot items) which is then tuned to the specific technology and application and updated with available data using a Bayesian approach. Failures due to wear-out, systematic and extrinsic root causes are considered separately.

In-orbit return from the fleets of the two satellite prime contractors ADS and TAS was collected and merged, allowing to provide reliability data for a list of standardized miscellaneous items typically used in satellite missions. A process for the derivation of similar data is defined for all items for which this approach has not been successful, e.g. because of insufficient sample size. This process can also be followed for items that are not standardized, prohibiting the use of In-orbit return as the main input for modelling.

System level reliability prediction

The existing approaches for system reliability prediction were generally considered sound and did not require any new developments during the study. An overview on the different existing methods is given, highlighting their strengths and limitations to provide guidance for method selection. In addition to this, the following aspects of system level reliability prediction were discussed specifically due to their relevance for space applications:

- Reliability assessment of phased missions to consider the sequence of relevant mission phases during the life of a space system

- Importance measures to direct efforts for reliability improvement to the components having the largest effect on system level reliability
- Reliability assessment of degraded systems to consider different levels of performance degradation as an input for risk assessment
- Quantitative modelling of common cause failures, e.g. resulting from systematic or extrinsic failure root causes
- System level considerations of wear-out with different models for wear-out modelling at component level

For the quantification of systematic failures, a model at satellite level has been developed based on major anomalies observed during the operation of satellites in-orbit. The model also allows a breakdown of the overall systematic anomaly rate by sub-system and/or severity (most anomalies having no impact on the mission).

Software failures can be considered as a special case of systematic failures, the largest concern being errors related to the requirement specification and/or the interface between hard- and software in a mixed system. Existing software reliability models focus on software development errors (assuming no errors related to the software specification) and do not provide reliable results for the low failure rates required for space applications. Therefore, the use of these existing models in the context of reliability prediction is not recommended. Note that in most of the times a full recovery from software errors is possible by uploading patches while the satellite is in safe mode.