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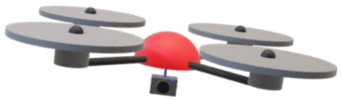

Risk-based Regulation of Unmanned Aircraft Systems

Mr Achim Washington | RMIT University

Dr Reece Clothier | Boeing Research and Technology

Dr Jose Silva | RMIT University

Contact : *achim_washington@hotmail.com*

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Background

- The aviation sector is rapidly evolving with the introduction of a number of new and novel airspace users.
- These users are plagued by a number of challenges that have resulted in the imposition of a significant amount of operational restrictions on them.
- The greatest non technical challenge facing the UAS industry is the lack of a suitable regulatory framework governing the safety of their operations [1, 2].
- It is widely acknowledged that the use of "off-the-shelf" approaches to aviation regulations are not suitable for the UAS industry [2].


[3]


[4]


[5]


[6]

Background

- Regulatory bodies are advocating the adoption of a “risk-based” approach to the development of regulations (e.g. FAA and EASA) [7]−[10] and recognising the need for a “risk-based” approach to the decision-making processes that is central to their compliance philosophies (e.g. FAA) [11].
- A particular challenge for new and novel aviation systems can be in taking the high uncertainty associated with these systems into consideration in the safety risk assessment and decision-making processes that underpin the “risk-based regulation” of the sector.
- Case study of UAS was chosen owing to the limited data and high uncertainty associated with these systems.

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Risk-based Regulation

- A risk-based approach is discussed in the context of the three aviation regulatory processes of: rule-making, compliance assessment, and compliance finding [12, 13].

Risk-based Regulation

Rule-making
The specification of regulations/ requirements

Compliance Assessment
Assessments against regulations/ requirements

Compliance Finding
The decision making process used to judge compliance

Risk-based Regulation

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Risk-based Regulation

Rule-making

The specification of regulations/ requirements

Describes how to develop and apply a suitable code of requirements that have traceability to, and are proportionate with, the degree of operational risk posed by a given aircraft system or sub-system.

Risk-based Regulation

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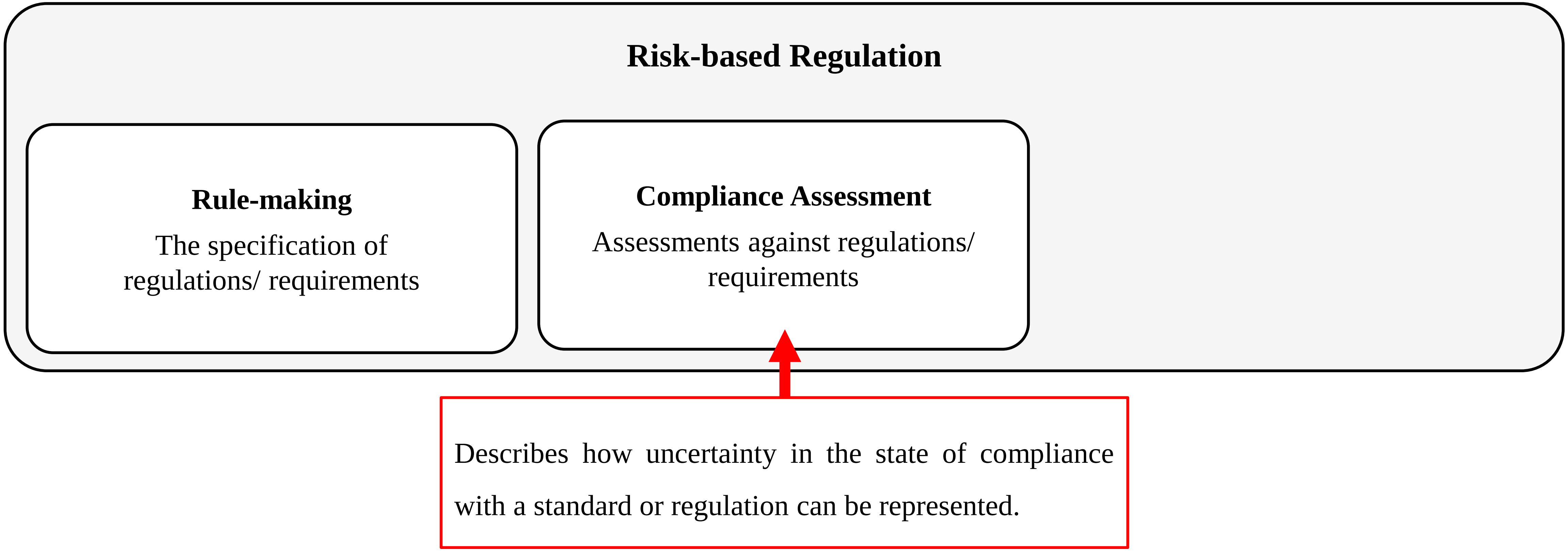

Risk-based Regulation

- A risk-based approach is discussed in the context of the three aviation regulatory processes of: rule-making, compliance assessment, and compliance finding [12, 13].

Risk-based Regulation

Rule-making
The specification of regulations/ requirements

Compliance Assessment
Assessments against regulations/ requirements

Compliance Finding
The decision making process used to judge compliance

Looks at how a decision with respect to the state of compliance of a system with regulatory requirements can be made on the basis of risk.

Risk-based Regulation - Current

- A risk-based approach is discussed in the context of the three aviation regulatory processes of: rule-making, compliance assessment, and compliance finding [12, 13].

Risk-based Regulation

Rule-making
The specification of regulations/ requirements

Compliance Assessment
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Compliance Finding
The decision making process used to judge compliance

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Risk-based Regulation - Proposed

- A risk-based approach is discussed in the context of the three aviation regulatory processes of: rule-making, compliance assessment, and compliance finding [12, 13].

Risk-based Regulation

Rule-making
The specification of regulations/ requirements

Compliance Assessment
Assessments against regulations/ requirements

Compliance Finding
The decision making process used to judge compliance

Such an extension is necessary to account for the uncertainty inherent in the state of compliance of an aviation system against a specific requirement.

Risk and Uncertainty

- High uncertainty in relation to the safety of UAS operations arises due to:
  - Relative infancy of the technology
  - Low flight hours
  - Complexity of the system
  - Changing baselines
  - Use of commercial off-the-shelf components

- Based on the literature review, it was concluded that existing aviation regulatory processes do not adequately account for uncertainty.

- Other industries like the nuclear power industry, space launch industry and environmental industry, take uncertainty into consideration in the risk assessment and risk management process.

System Safety Regulations

System Safety Regulations

Part 1309 regulations are intended to supplement prescriptive standards on the design, manufacture, and installation of aircraft components. At a high-level, system regulations specify the requirement for [15]:

- A documented analysis showing that equipment and systems perform as intended under foreseeable operating and environmental conditions;
- The adoption of principles from fail-safe and fault-tolerant design; and
- The demonstration (through a documented qualitative or quantitative analysis) that the expected frequency of failure of equipment and systems, when considered separately and in relation to other systems, is inversely-related to the severity of its effect on the safe operation of the system. This is commonly referred to as the system safety performance requirement (SSPR).

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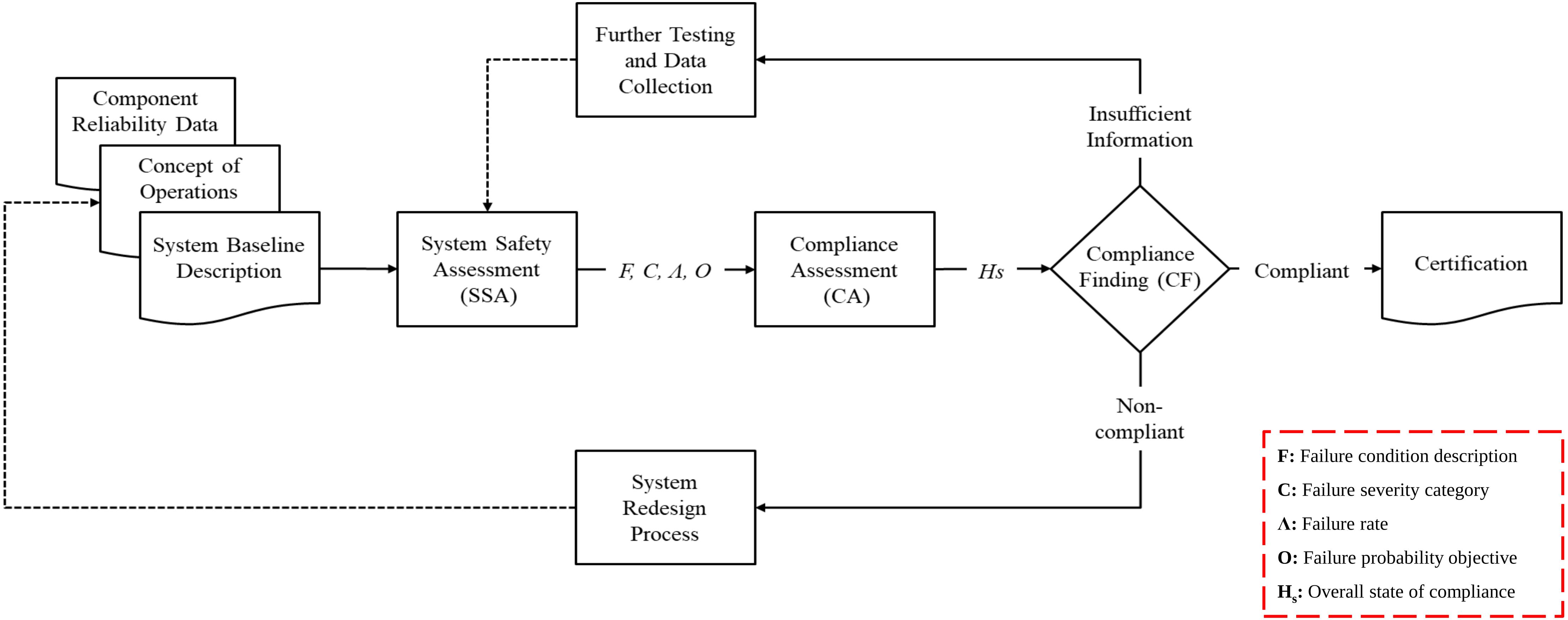
The focus of this work is on the third requirement, that is the SSPR Compliance Process

Traditional SSPR Compliance Process

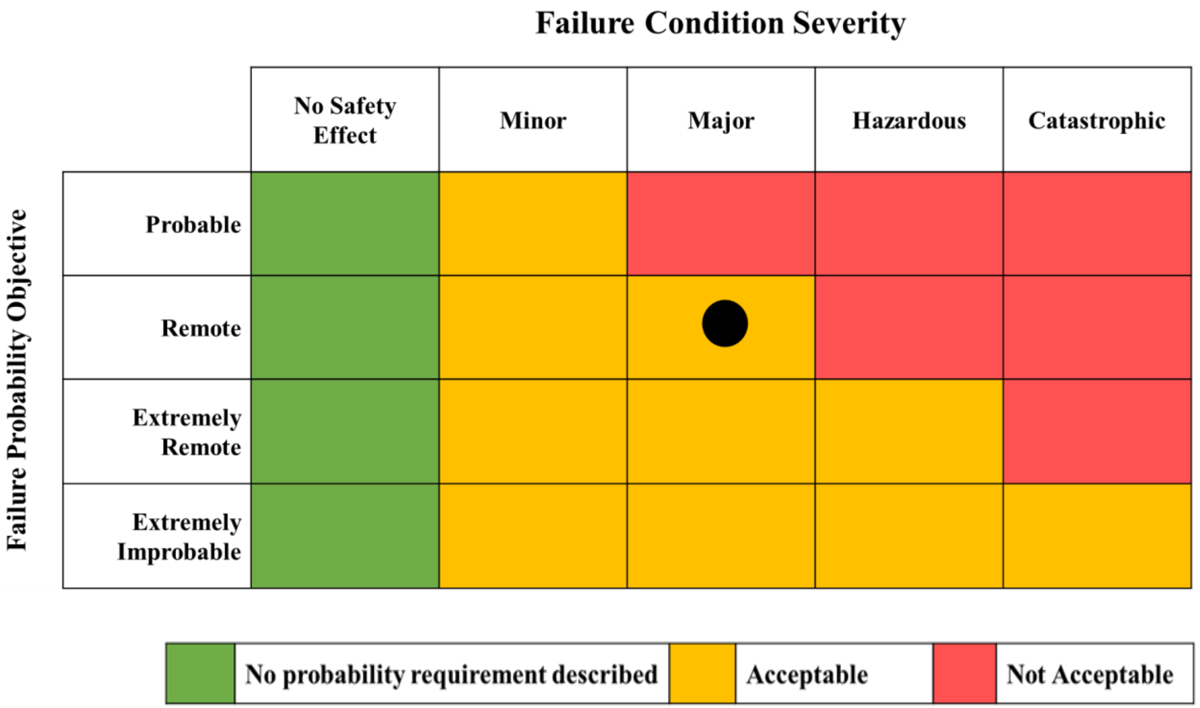
The traditional SSPR compliance process follows the framework presented below [16]



Traditional SSPR Compliance Process [16]

Traditional SSPR Compliance Process - Output

Traditional SSPR Compliance Process showing a point value assessment of λ_n of the APFH for a given failure.



Traditional SSPR Compliance Process [17]

Outputs from the SSA process for a single failure condition

f_1 : "*failure condition description*"

c_1 : "*Major*" (worst case consequential outcome)

λ_1 : "*point estimate of failure rate*"

o_1 : "*Remote* (< 10^{-4} hr^{-1})"

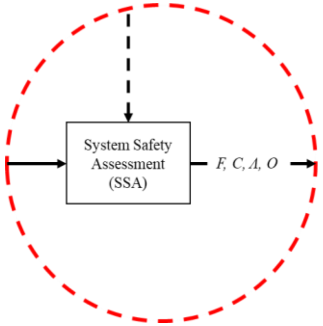
CA process makes use of a deterministic binary "pass or fail" process [16]

$$H_n = \begin{cases} True & \text{if } |\lambda_n| \leq o_n \\ False & otherwise. \end{cases}$$

Traditional SSPR Compliance Process – Limitations

System Safety Assessment Process

- Uncertainty in the data is **not** taken into consideration.
- Uncertainty is **not** captured in the outputs of the SSA process.
- Only point estimates of the Average Probability per Flight Hour (APFH) are provided.
- Makes the assumption of a “**worst-case**” consequential outcome.

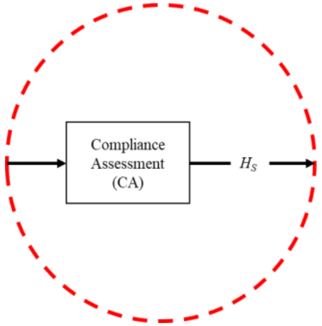


Limitation A

Compliance Assessment Process

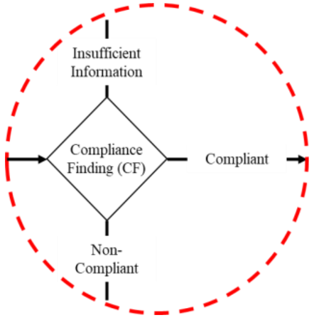
- The output of the CA process are **binary statements** (True/False) without consideration for uncertainty in the state of compliance.

Limitation B



Compliance Finding Process

- There is **no mathematical framework** for making compliance findings in the presence of **uncertainty.**

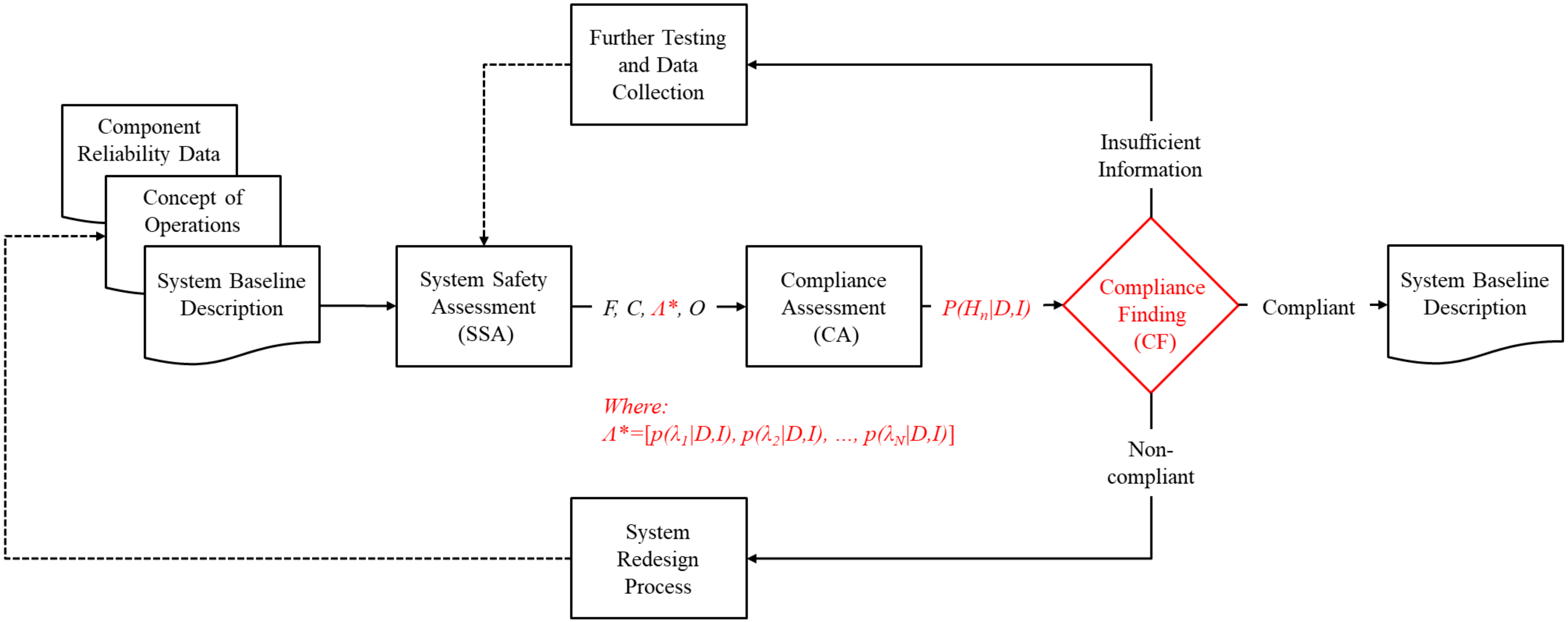


Limitation C

Problem - Not possible to make objective compliance findings in cases of high uncertainty

Extended SSPR Compliance Process

The extended SSPR compliance process follows the framework presented below [16]:



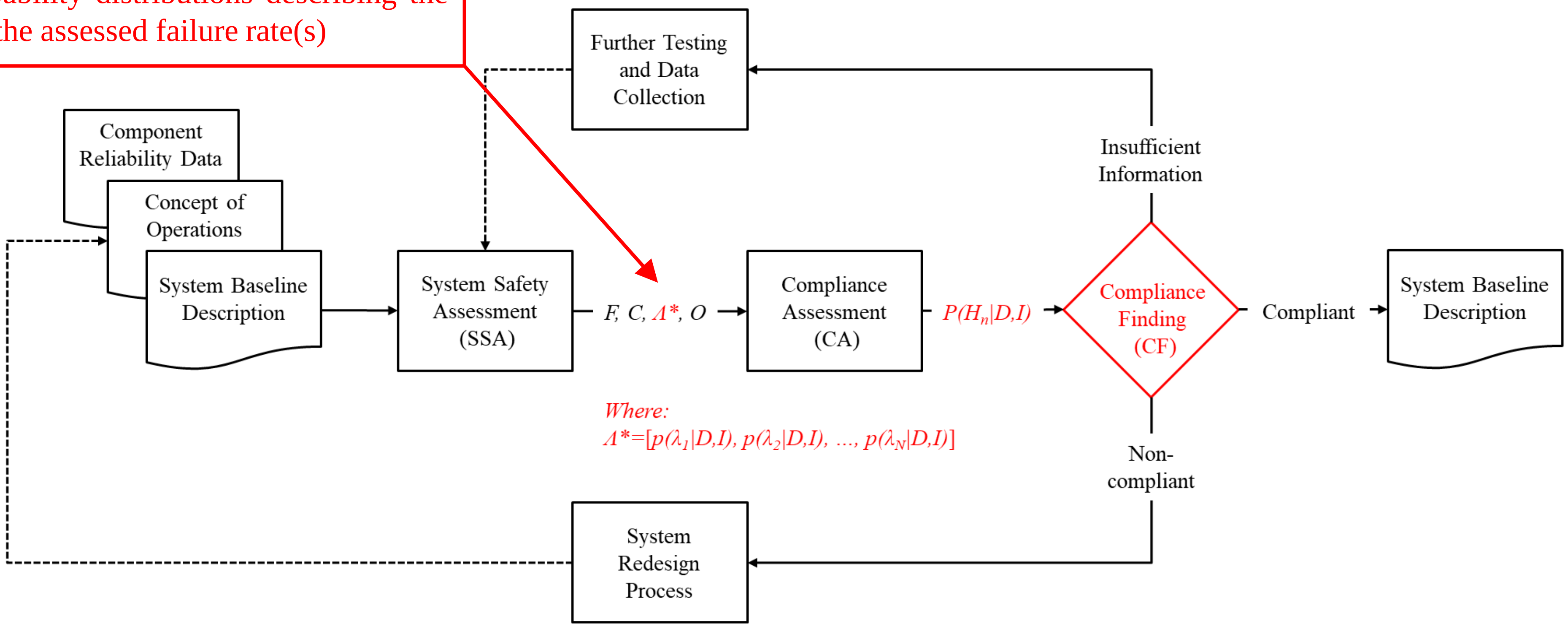
Extended SSPR Compliance Process [16]

Extended SSPR Compliance Process

The extended SSPR compliance process follows the framework presented below [16]:

Approach - Bayesian Analysis.

Output - probability distributions describing the uncertainty in the assessed failure rate(s)



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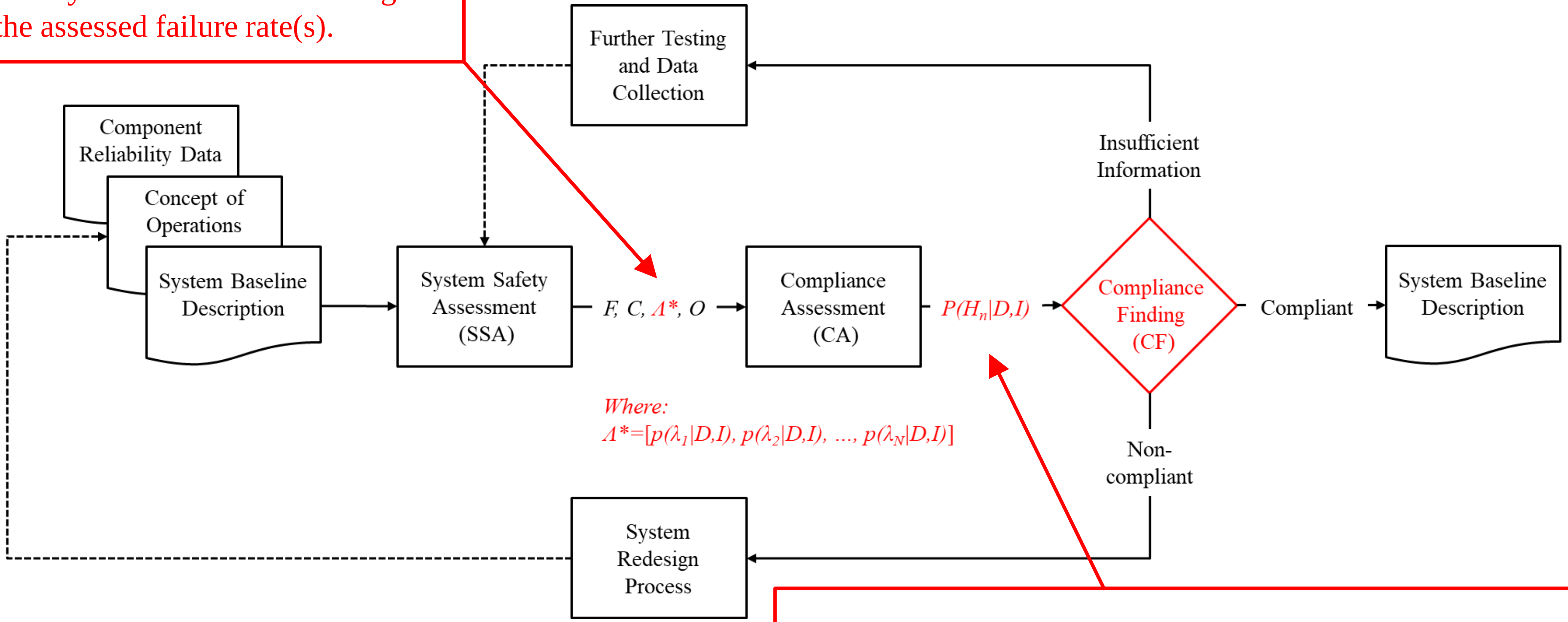


Approach - Bayesian Hypothesis Test.

Output - probabilities describing uncertainty in the state of compliance.

Extended SSPR Compliance Process

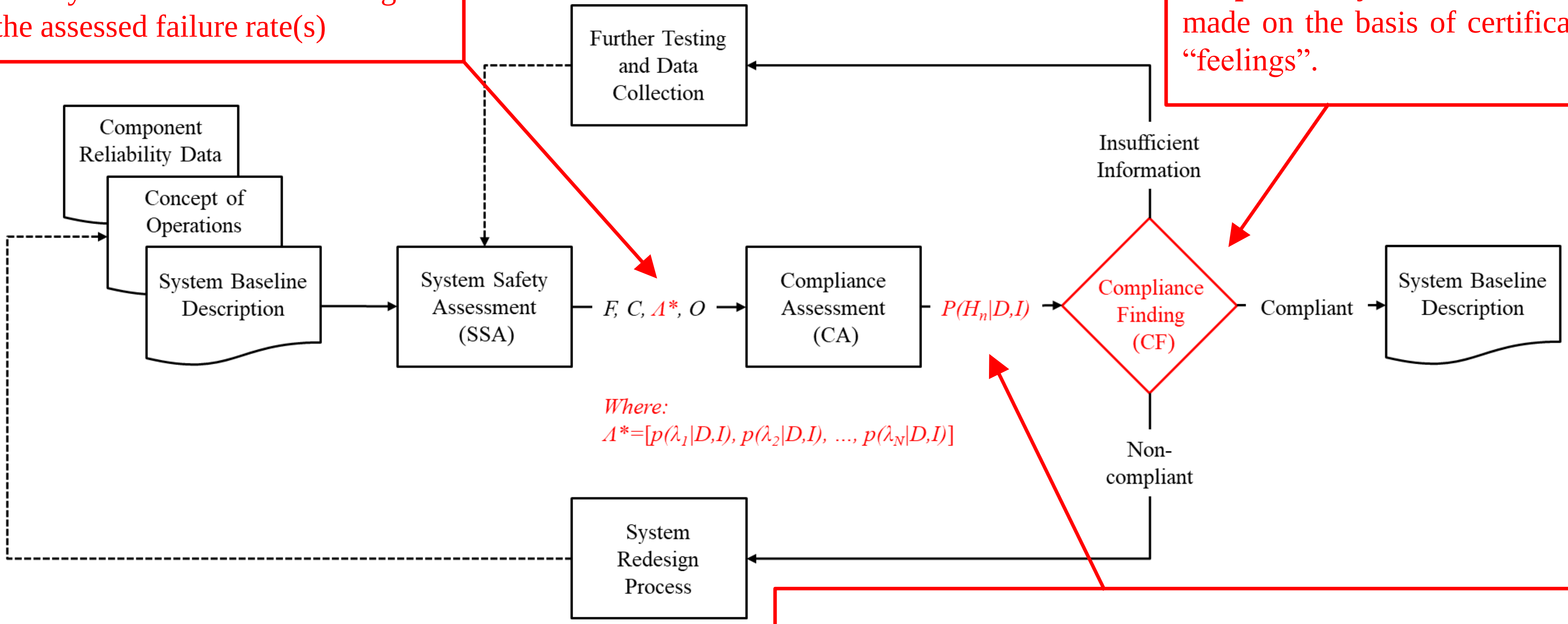
The extended SSPR compliance process follows the framework presented below [16]:

Approach - Bayesian Analysis.

Output - probability distributions describing the uncertainty in the assessed failure rate(s)

Approach – Normative Decision Theory.

Output - Objective CF decisions can be made on the basis of certification risk not "feelings".



Approach - Bayesian Hypothesis Test.

Output - probabilities describing uncertainty in the state of compliance.

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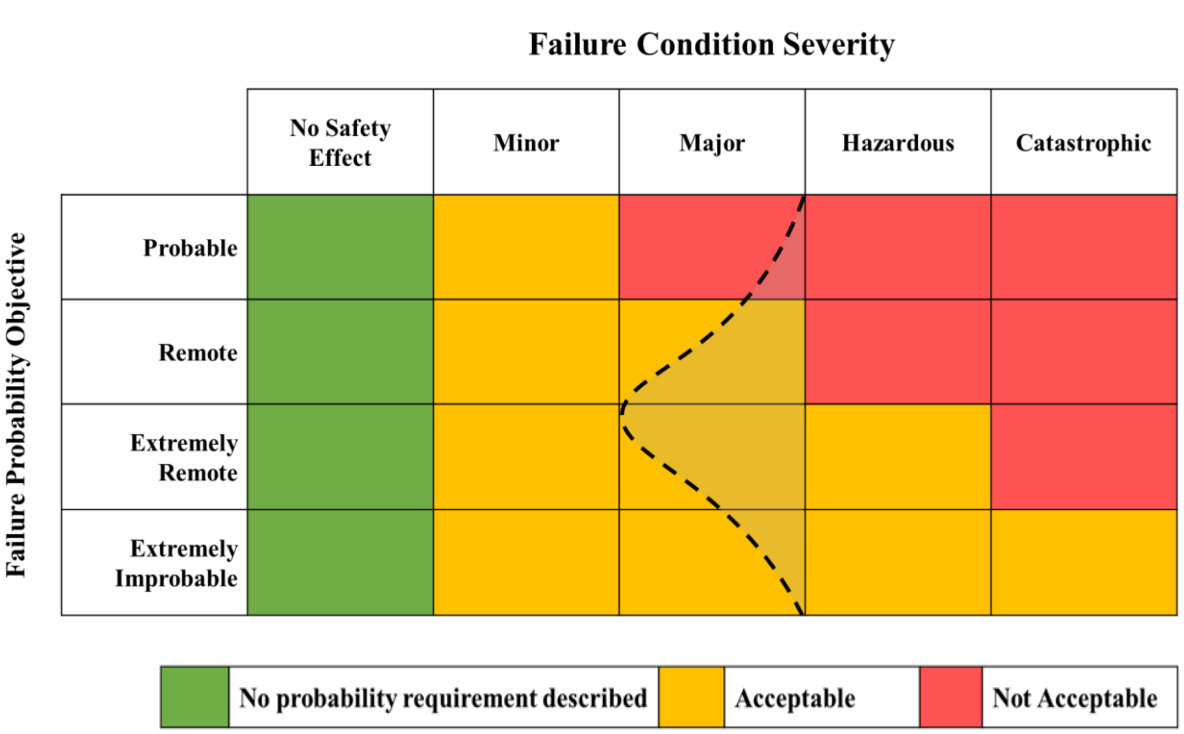
Extended SSPR Compliance Process - Output

Extended SSPR Compliance Process showing a probability distribution describing uncertainty in the state of compliance for a given failure.



Extended SSPR Compliance Process [17]

Outputs from the SSA process for a single failure condition

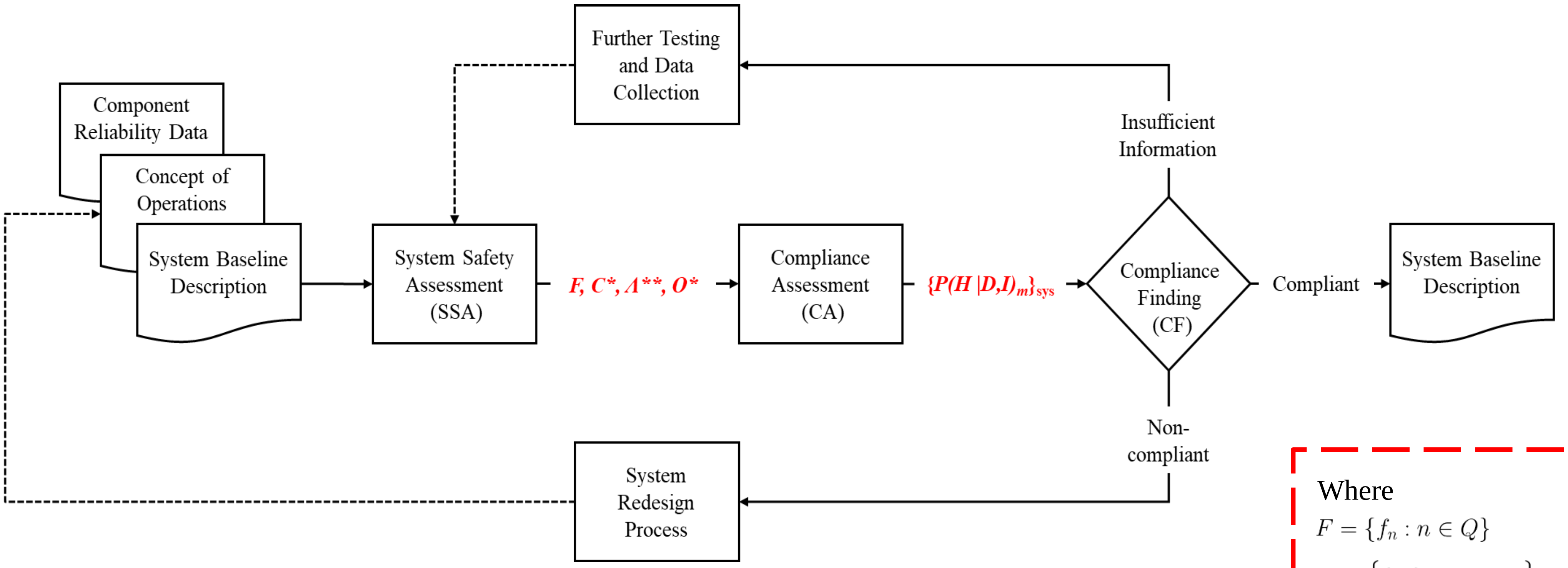
f_1	: "*failure condition description*"
c_1	: "*Major*" (worst case consequential outcome)
$p(\lambda\|D,I)_1$	: "posterior probability distribution"
o_1	: "*Remote* (< 10^{-4} hr^{-1})"

CA process makes use of Bayesian hypothesis testing [16]

$$P(H_n|D,I) \quad = \quad \int_0^{O_n} p(\lambda_n|D,I).d\lambda$$

Proposed SSPR Compliance Process

The proposed SSPR compliance process follows the framework presented below [17]:



Where

$F = \{f_n : n \in Q\}$

$C^* = \left\{\{c_m\}_{sys}, m \in R\right\}$

$\Lambda^{**} = \left\{\{p(\lambda|D, I)_m\}_{sys}, m \in R\right\}$

$O^* = \left\{\{o_m\}_{sys}, m \in R\right\}$

Proposed SSPR Compliance Process [17]

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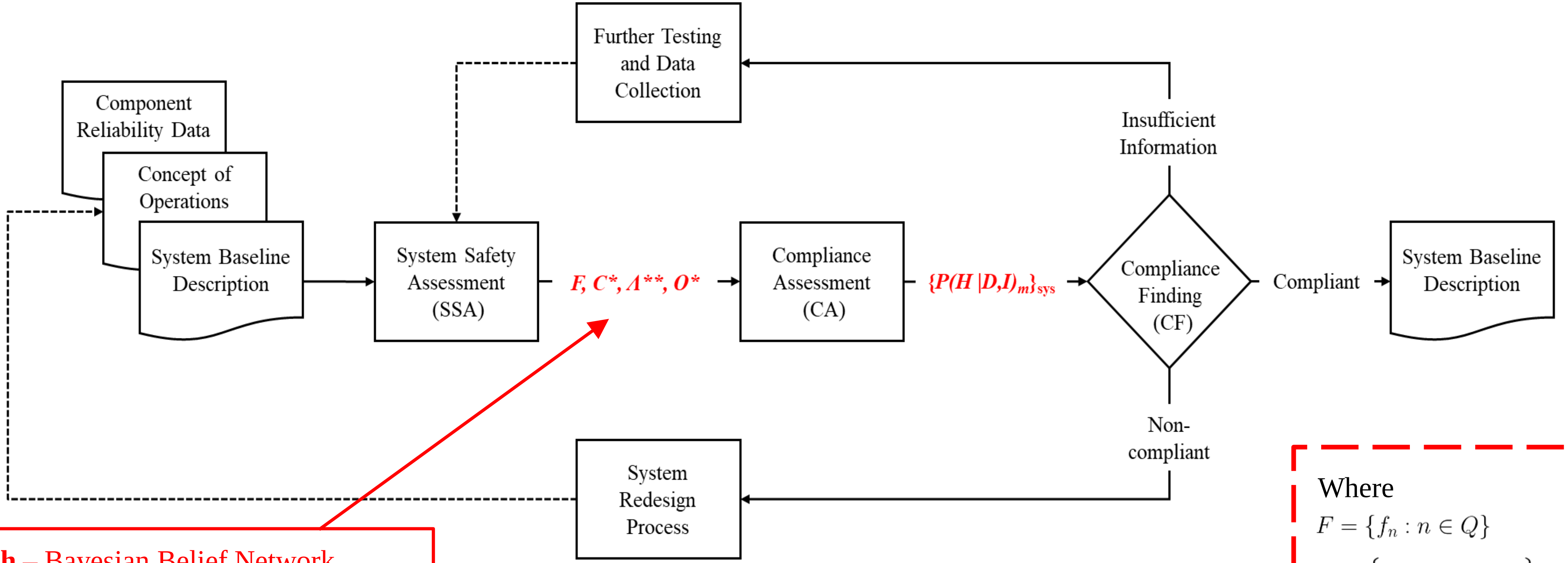


Approach – Bayesian Belief Network.

Output - probability distributions describing the uncertainty in the assessed failure rate(s) for each failure condition severity.

Proposed SSPR Compliance Process [17]

Where

$F = \{f_n : n \in Q\}$

$C^* = \left\{\{c_m\}_{sys}, m \in R\right\}$

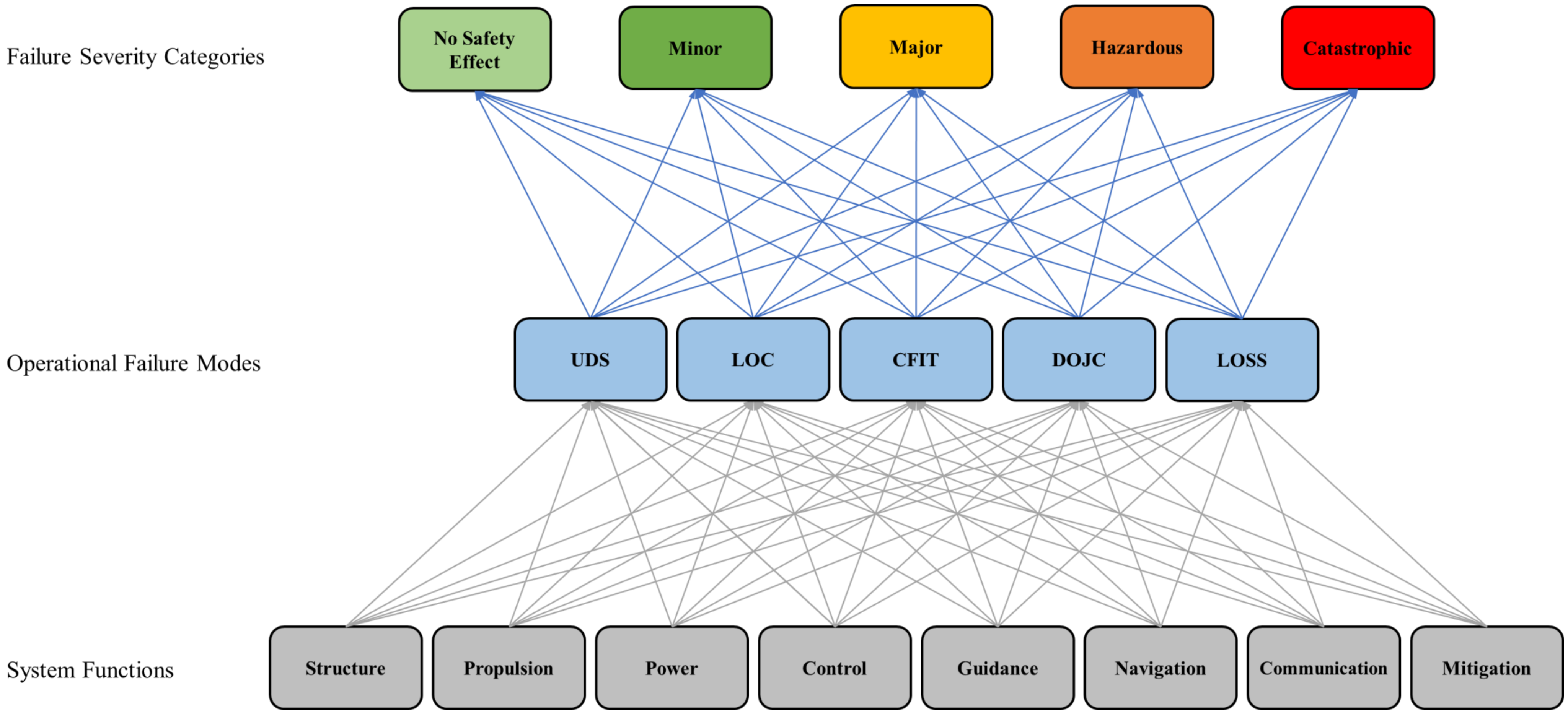
$\Lambda^{**} = \left\{\{p(\lambda|D,I)_m\}_{sys}, m \in R\right\}$

$O^* = \left\{\{o_m\}_{sys}, m \in R\right\}$

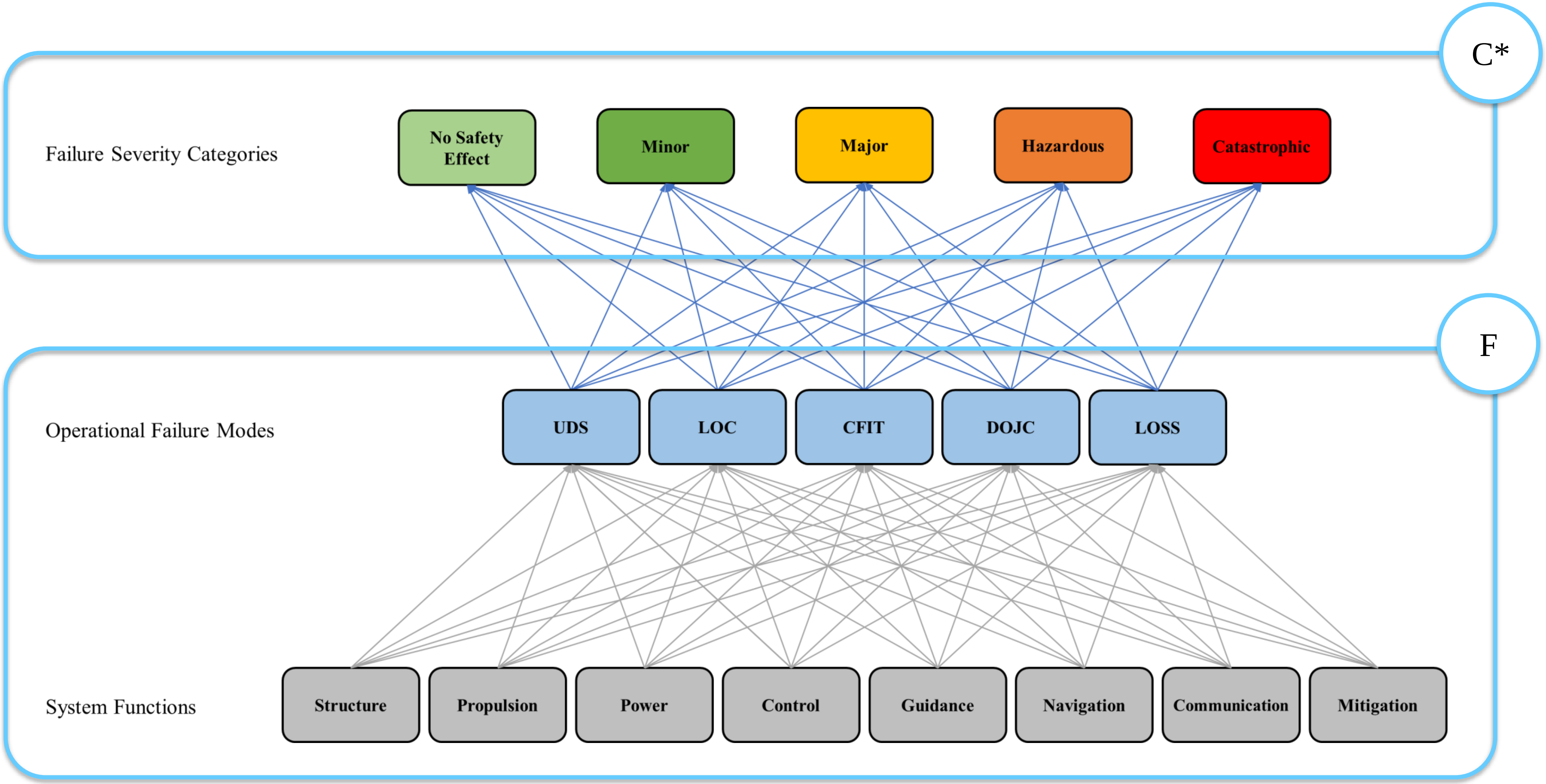
Proposed SSPR Compliance Process – BBN [17]

Failure severity category
Operational failure modes
System functions

Proposed SSPR Compliance Process – BBN [17]



Proposed SSPR Compliance Process – BBN [17]

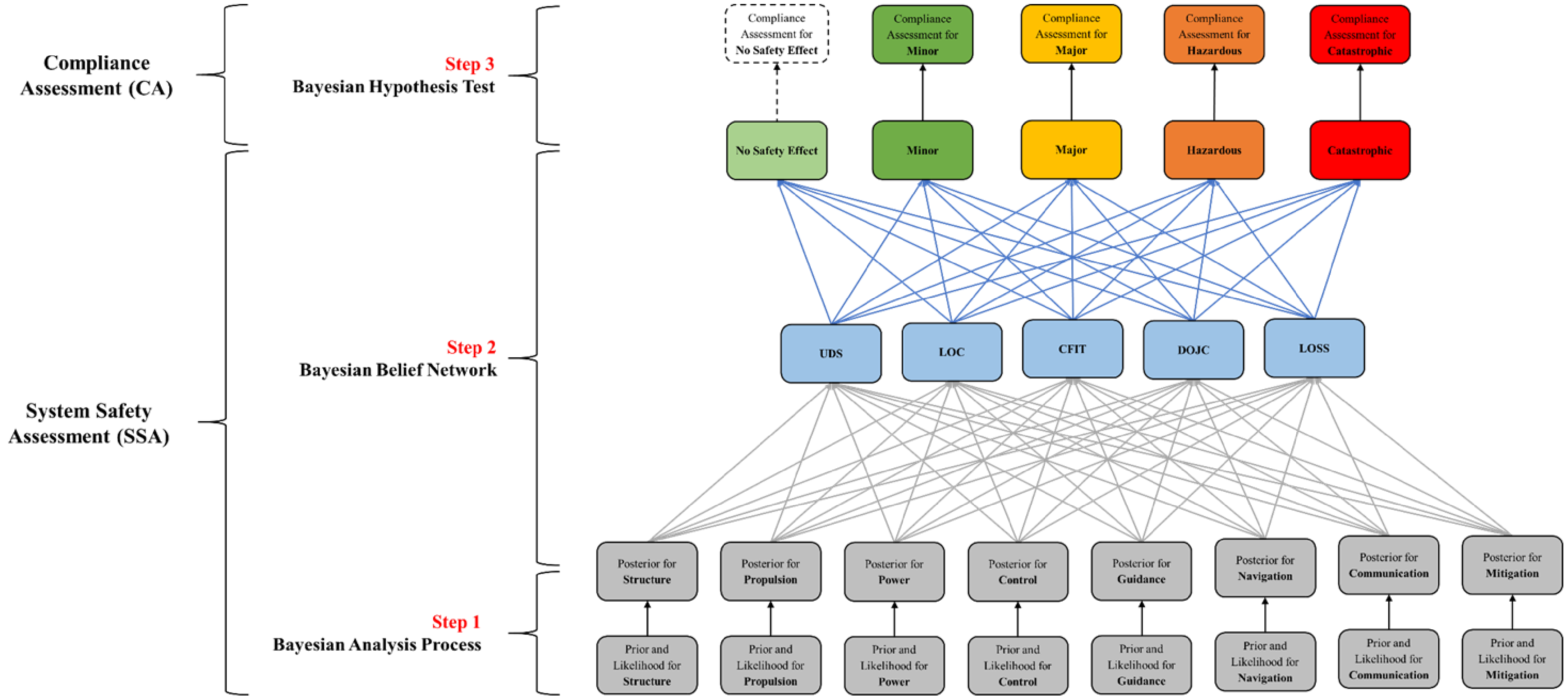


Proposed SSPR Compliance Process – BBN [17]

Advantages of BBN [13]

- They explicitly model causal factors;
- Allow for reasoning from effect to cause and vice versa;
- Reduce the burden of parameter acquisition;
- Allow for previous beliefs to be overturned in light of new evidence;
- Make predictions with incomplete data;
- Combine diverse types of evidence including both subjective beliefs and objective data and arrive at decisions based on visible, auditable reasoning;
- Allow for modelling of complex relationships with multiple dependencies;
- Are capable of be being used in the presence of scarce data

Proposed SSPR Compliance Process – BBN [17]



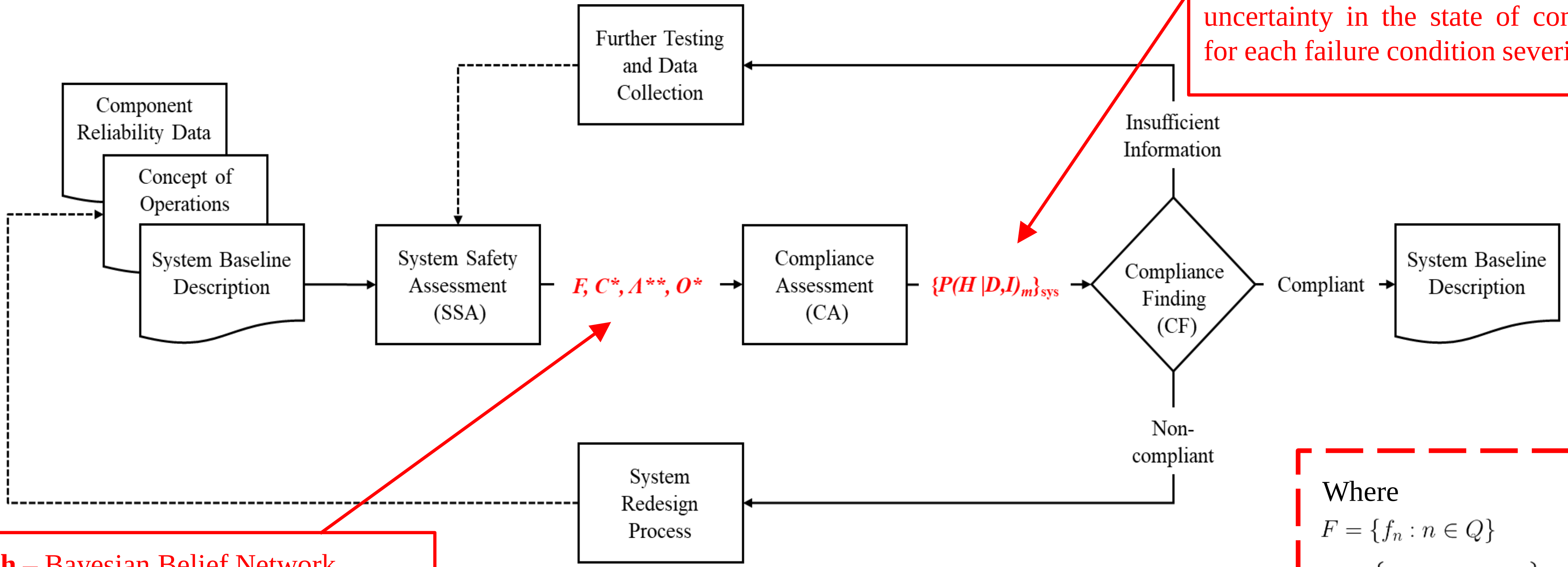
UDS – Unpremeditated Descent Scenario **LOC** – Loss of Control **CFIT** – Controlled Flight into Terrain **DOJC** – Dropped or Jettisoned Components **L0SS**- Loss of Safe Separation

Proposed SSPR Compliance Process

The proposed SSPR compliance process follows the framework presented below [17]:

Approach – Bayesian Hypothesis Test.

Output - probabilities describing uncertainty in the state of compliance for each failure condition severity.



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Where

$F = \{f_n : n \in Q\}$

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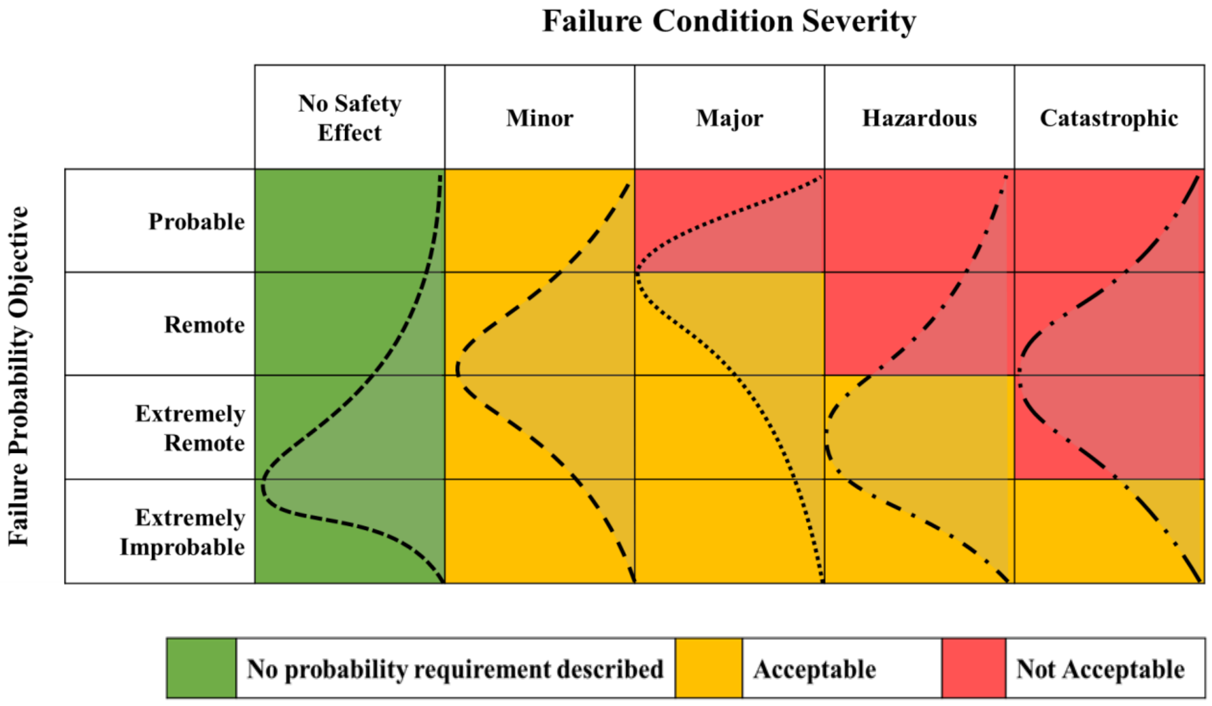
Proposed SSPR Compliance Process – Output

Proposed SSPR Compliance Process showing a probability distribution describing uncertainty in the state of compliance for a given failure.



Proposed SSPR Compliance Process [17]

Outputs from the SSA process for a single failure condition

F : "*failure condition descriptions*"

*C** : "No Safety Effect, Minor, Major, Hazardous, Catastrophic"

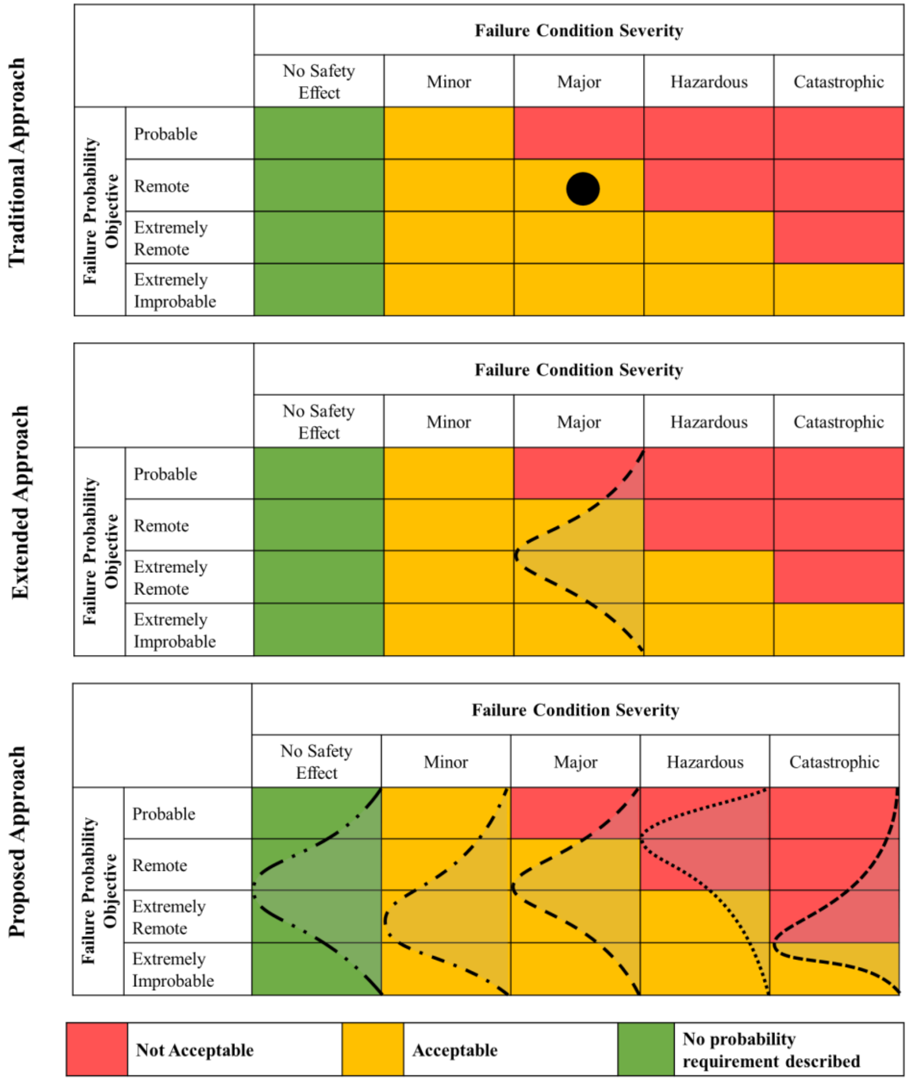
*Λ*** : "posterior probability distributions"

o_1 : "*Probable* (< 10^{-3} hr^{-1}), , *Remote* (< 10^{-4} hr^{-1}), *Extremely Remote* (< 10^{-5} hr^{-1}), , *Extremely Improbable* (< 10^{-6} hr^{-1}), "

CA process makes use of Bayesian hypothesis testing [17]

$$P(H_{m,n}|D,I) = \int_0^{O_{m,n}} \{p(\lambda_m|D,I)\}_n \, .d\lambda$$

Evolution of Outputs from the SSA Process [12, 13, 17]



Traditional Approach

"Level 3" treatment of uncertainty according to Paté-Cornell's "six levels of treatment of uncertainties in risk analysis" [18].

Extended Approach

"Level 4" treatment of uncertainty according to Paté-Cornell's "six levels of treatment of uncertainties in risk analysis" [18].

Proposed Approach

"Level 5" treatment of uncertainty according to Paté-Cornell's "six levels of treatment of uncertainties in risk analysis" [18].

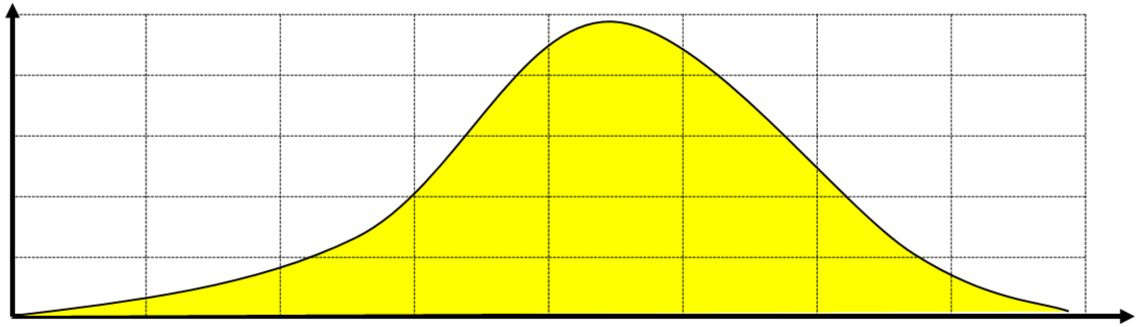
Future Work & Summary

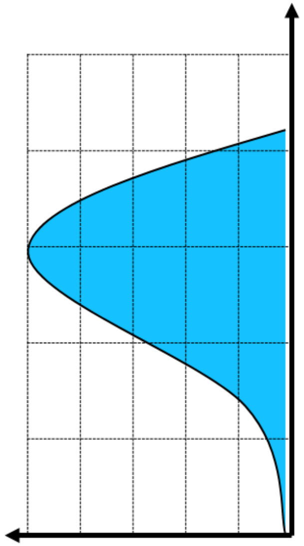
Future Work

There are a number of avenues for future research including [12]:

- Providing a theoretical approach for accounting for data uncertainty (e.g., inaccurate, censored or missing, etc.) input to assessment processes (e.g., failure rate data);
- Identifying and characterising the uncertainties within the ALARP and SFARP decision-making frameworks;
- Determining how a normative decision-making approach can be adapted to account for ALARP and SFARP decision making principles, and the uncertainties inherent to them;
- Application of the general approach to other aviation sectors (e.g., space launch, UAM, *etc*.), and regulations;
- Working in partnership with an industry applicant and NAA, validate posited benefits of the approach through its use as an alternate means of compliance.

Future Work - Overall Objective of the Model





	No Safety Effect	Minor	Major	Hazardous	Catastrophic
Probable					
Remote					
Extremely Remote					
Extremely Improbable					

Incorporation of uncertainty into the failure probability objectives and the failure severity categories

Summary

- **This overall research**:
  - Broadens the current understanding of “risk-based regulation” to include a “risk-based” approach to: rule-making, compliance assessment and compliance finding;
  - Provides a systematic means of taking the uncertainty associated with each of these processes into consideration through the adoption of various Bayesian analysis techniques.
- Improves regulatory outcomes under the new paradigm of risk-based regulation, through providing a conceptual framework for the rational, transparent and systematic treatment of uncertainty in the risk assessment and regulatory decision-making process.

The mathematics/theory is simple (nothing Earth shattering here) but its application to system safety certification would be an revolutionary step change over current aviation certification practices.

Questions?

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