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Assessment of Technical Airworthiness in Military Aviation: Implementation and Further advancement of the Bow-Tie Model

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Abstract

International Civil Aviation Organization (ICAO) Standards and Recommended Practices (SARPs) serve to harmonize the safety regulation of civil aviation around the world. ICAO SARPs are only applicable to countries signatory to the 1944 Chicago Convention and only to civil aircraft operations. There is no complimentary international organization providing the same standardization of military aviation regulations. NATO provide international standards for interoperability, and the EDA now provide a militarized European regulatory set aimed at harmonizing requirements for European militaries, however there is no political platform to extend this beyond a voluntary adoption, particularly beyond the European Union. Each military aviation regulator has developed a unique airworthiness regulatory system. There is no recognized method for unbiased assessment and comparison of the disparate regulatory frameworks. This poses a significant challenge when establishing acceptance between military regulatory authorities. This paper develops an assessment framework based on assuring technical integrity utilizing a novel implementation of bow-tie methodology. Further, a unique visualization method is presented to facilitate the comparative assessment of the different regulatory frameworks. This visualization method is a powerful tool for conveying the regulator interaction with the organizations performing design, production and maintenance under their regulatory framework.

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Keywords: Airworthiness, Military, Bow-Tie, Technical Integrity, Recognition, PBP Bow-Tie, Framework

1. Introduction

ICAO provides the principles and rules for all Civil Aviation bodies, to which all United Nations subscribe. Throughout the evolution of civilian aviation safety there has been a constant drive by ICAO to assure all aspects of airworthiness are regulated and safe. The latest evolution focuses on holistic safety oversight through the Universal Safety Oversight Assurance Program [1]. The aim of this program is to provide global oversight, and audit the performance of core elements affecting aviation safety; namely

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legislation, organization, licensing, operations, airworthiness, accident investigation, air navigation services and aerodromes [2]. However, ICAO Standards and Recommended Practices (SARPS) are not applicable to state aircraft, in fact they are pointedly excluded in Article 3 if the Chicago Convention; *"This Convention shall be applicable only to civil aircraft, and shall not be applicable to state aircraft. Aircraft used in military, customs and police services shall be deemed to be state aircraft*". There is no truly international organization comparable in function to that of ICAO for Military Aviation.

Evolution of military aviation safety is typically reliant on the interaction between Military Airworthiness Authorities (MAA) and their cognizance of changes within ICAO (e.g. integration of Safety Management Systems), to identify where improvements can be made. An easily recognizable shortfall of this practice is the absence of an assessment standard. To this end, the European Defence Agency (EDA) has established pathways for recognition of other military airworthiness systems, titled the European Military Airworthiness Document – Recognition (EMAD-R) [3]. Based on its multinational impact, several benefits will be seen within the European Union (EU), most notably with the acceptability of design, product and maintenance certification between countries, increasing the applicability of EU defense industry. Apart from financial benefits, there are several important safety benefits that can be realized through recognition. Unfortunately, for non-European militaries the EDA process has a heavy reliance on a known implementation level for the recently developed European Military Airworthiness Requirements (EMARs). This is not easily transferrable to non-EU militaries. A review of key western military airworthiness frameworks and their interaction through collaborative forums please refer to the review by Purton et al [4].

While airworthiness should be considered holistically, and encapsulate the full spectrum of design, production, maintenance, operations, logistics and support services, the global focus for military recognition is currently technical airworthiness (design, produce, maintain). A holistic military airworthiness system should ideally encapsulate all of these elements, under a risk-based assessment employable by the capability managers. This airworthiness risk management and acceptance approach would enable the use of aircraft when operational necessity occurs, as opposed to the civil aviation restrictive approach on un-airworthy aircraft. Development of a system to assure technical integrity, the under pinning principle for assuring technical airworthiness, is a complicated and extensive task. This cannot be achieved without prior development of a supporting structure that clearly articulates and separates the requirements. Airworthiness is defined as "*Airworthiness is a concept, the application of which defines the condition of an aircraft and supplies the basis for judgment of the suitability for flight of that aircraft, in that it has been designed, constructed, maintained and operated to approved standards and limitations, by competent and authorized individuals, who are acting as members of an approved organization and whose work is both certified as correct and accepted on behalf of Defence.*" [5]. The definition highlights that a model for assessing airworthiness must encompass the technical design, construction/production and maintenance of the item within a system of competent processes and people.

The primary objective of a technical airworthiness regulatory system is to control the loss of technical integrity. Technical integrity is defined as *"Technical integrity addresses the management of barriers to major accident events that would be harmful to people or environment"* [6]. Modeling tools used in system safety assessments provide an ideal platform for controlling the potential loss of technical integrity lends. Assessment methodologies include: Fault and Event Tree Analysis, Failure Mode and Effects Analysis, Operating and Support Hazard Analysis, Barrier Analysis or Layer of Protection Analysis [7-16]. These tools could be used for the development of an appropriate military airworthiness framework. One particular approach, which offers a method for the systematic assessment based on an amalgamation of fault/event tree and barrier analysis, is the bow-tie model [15, 17-22]. Traditionally, a bow-tie model lists a top event; for instance, an aircraft mishap[a]. Input to the method is a set of potential causal events leading to the mishap (e.g. maintenance error leading to engine failure). A set of barriers for each causal failure sequences are determined, with each barrier corresponding to a mechanism for reducing the likelihood of the mishap occurring (e.g. standardized maintenance job sheets, maintenance cross-checks, training, and pre-flight inspections). Given the occurrence of the mishap, a series of consequence sequences can also be determined. A set of controls for each consequence sequence are determined, with each identified control corresponding to an opportunity to reduce the likelihood and the magnitude of the consequences given the occurrence of the mishap (e.g. crashworthiness features, operational restrictions and recovery procedures). The resulting model can be visualized as a bow tie, with the initiating failures on the left, the mishap at the center, and the consequence sequences on the right (Figure 1). The model is given its name because of the identifiable shape of its visualization.

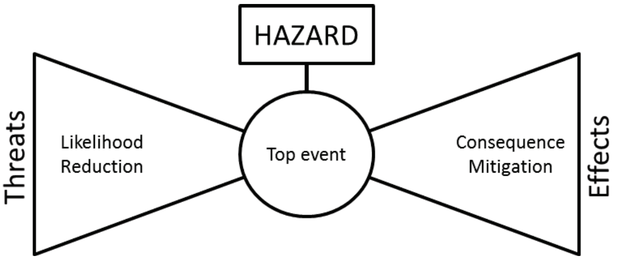

Figure 1: Basic Bow-tie illustrating the threats to the undesired top event being prevented from occurring on the left and the effect of the triggered hazard being mitigated on the right.

1.1. Integrity Lines

By simplifying Bale and Edward's definition of technical integrity [23]; technical integrity is assured through integrity in the areas of product, behavior and process. For instance, an engineer designing an aeronautical product to a set of standards (product integrity), must be assessed as competent and qualified (behavior integrity) and be following approved processes (process integrity). These three components of technical integrity define the immediate areas of influence on a technical item. These integrity areas can be applied to the threat lines of the Bow-Tie, from here on called integrity lines, not areas, to fit with the development of the Bow-Tie model. Further, each integrity line can be separated into distinguishable phases of the technical lifecycle: design, production and maintenance (or sustainment in a broader sense). Intrinsic to these areas are management and supply, each able to influence the lifecycle zones.

This research identifies an assessment framework that, while focusing on the technical domain, is generalized enough to be transferred to both technical and operational airworthiness spectrum, and indeed any other technical regulatory system. A unique application and adaption of the bow-tie model is presented, which provides a novel and generic way for representing technical integrity assurance provided by military airworthiness systems. A visualization of the model, combining the technical integrity definition and technical item lifecycles, is illustrated in Figure 2.

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[a] An aviation incident or accident that may or may not result in damage

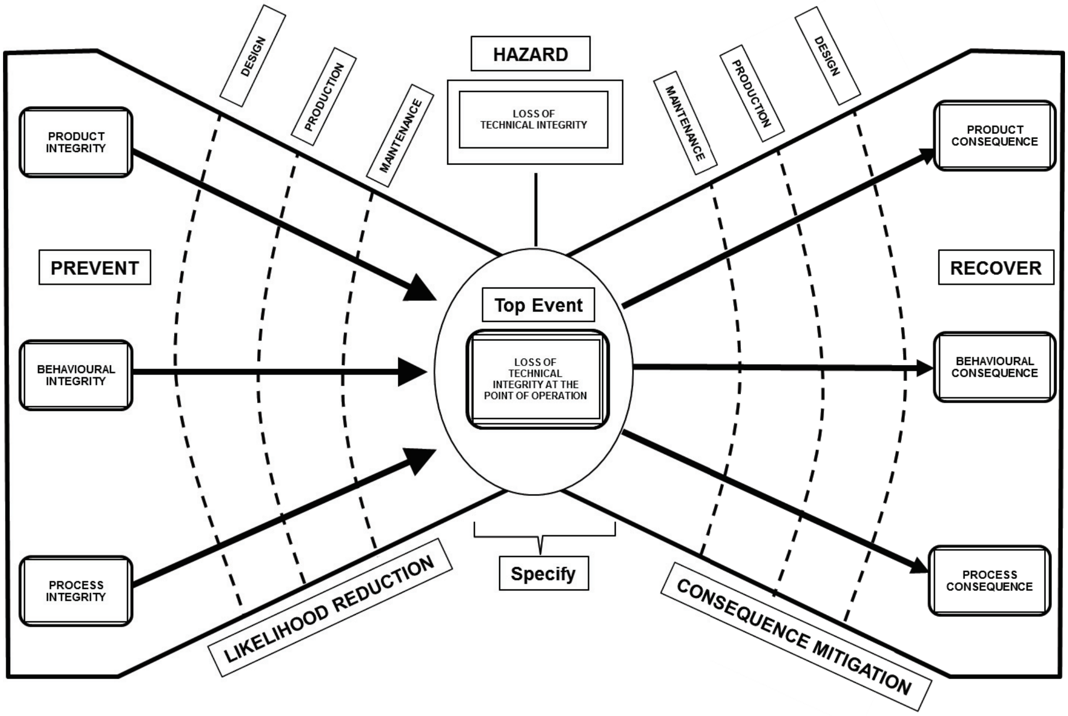

Figure 2: A composition of the bow-tie methodology overlapped with the technical integrity definition and technical item lifecycle, this framework is given the title the Product-Behavior-Process (PBP) Bow-Tie.

Developed within the paper is an activity axiom that can be readily applied at any stage of the technical lifecycle. The activity axiom develops a process for satisfying the requirements of an attestation. It is repeatable and forms the barriers for the Product-Behavior-Process (PBP) Bow-Tie. The use of independence of the attestation as a method for providing fidelity within the assessment is justified and explained. The preliminary implementation is focused solely on the preventative barriers (Left Hand Side of the Bow-Tie) of the unique Product-Behavior-Process (PBP) Bow-Tie. This paper describes the PBP Bow-Tie model and its use for describing the technical integrity provided by different regulatory systems/frameworks. A unique visualization that offers a method for comparing assessments of different regulatory frameworks is also presented. The approach/model is then used to evaluate the European Aviation Safety Agency (EASA), Australian Defence Force (ADF), United States (US) Army, US Navy and United Kingdom (UK) technical regulatory frameworks.

2. The PBP Bow-Tie Model

The bow-tie model has gained wide regard as a tool for communicating risk across all levels of the workforce [17, 20, 24, 25]. The bow-tie model provides a readily understood visualization of the relationships between the causes of loss of integrity, the escalation of such events, the controls reducing the likelihood of the event from occurring and controls put in place to limit the consequence [26]. It can be considered an adapted combination of Event and Fault Tree Analysis [14, 15] and Barrier Analysis [8, 9, 11, 12, 18, 27, 28], and can be applied qualitatively [15, 17, 20, 29] or quantitatively [19, 21, 22]. The traditional bow-tie diagram can be applied to many situations; Lewis and Smith [20] identify that there are many published applications within Governments and Governmental organizations, for example; the UK Defense Industry for safety cases [24] and the French Government for risk analysis [25].

2.1. Integrity at Phases in the Technical Lifecycle

The bow tie model can be adapted to provide a metric for assessing the technical integrity provided by a regulatory framework. This process begins by defining the technical lifecycle. At the highest level, the process begins with the design phase, moves into production, and is followed by the through life support (or maintenance) phase, and finally the retirement phase[b]. At all times this lifecycle is supported through supply chains and influenced by management. Figure 3 illustrates the lifecycle with input from supply and influence from management. Not shown are the potential lines of feedback, where, for example, experience gained in the maintenance of operational systems influences the design and in-turn production of other systems.

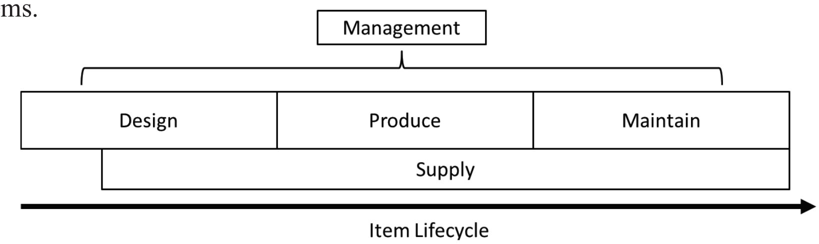

Figure 3: The technical item lifecycle; first designed, then produced (manufactured or constructed) then maintained. Supply of material is required during design through to maintenance activities. Management reserves the right to influence the lifecycle.

The lifecycle process is scalable and hierarchical, i.e., there is no restriction on the size of the item, or the number of times it occurs, and no preclusion on this occurring on a smaller scale within a larger lifecycle process. For instance, when designing an aircraft wing it may be realized during production that some design rectification is required, instigating a smaller re-design, then production and maintenance utilized during testing of the re-design, before the wing lifecycle continues. This one, many, innumerable mantra is fundamental in identification of the lifecycle activities; for instance, within operations the lifecycle may be conceptualize then plan and finally execute.

This lifecycle continuum applies to each of the components of technical integrity. As highlighted, product integrity of the aircraft wing is checked, a deficiency is identified and the wing is returned to the design activity. However, to assure the product integrity is maintained it is important that the design, production or maintenance is carried out by competent, trained and authorized personnel following approved processes. That is, the person conducting the re-design of the wing, should have a standard identified for the qualifications, training and experience required for that position, and the person should be checked against that standard. Further, during the design, only approved processes should be utilized. The product, behavior and process integrity need to be monitored at each phase of the technical lifecycle to ensure there is no loss of technical integrity. This was illustrated in Figure 2.

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[b] The retirement phase is not considered in this research as loss of technical integrity of the item in retirement will not cause an aircraft mishap.

2.2. Axiomatic Test Points

At certain points within the certification process attestations are made against defined standards to verify that all requirements detailed in those standards have been achieved, and where they have not, the deficiencies and proposed rectifications are identified. There is a routine to the attestation process, that is, the same steps can be followed to provide an accurate and justifiable attestation. It follows the same five steps; firstly, an attestation requires a standard or set of conditions describing the ideal state of the product, person or process at each particular phase of the technical lifecycle. This standard can be defined by an external organization or can be a benchmark or checklist defined internally. Secondly, progressive inspection against the standard may be required. Next, a test against the standard is carried out and then all deficiencies are identified and proposals made for rectification or acceptance of those deficiencies. Lastly, an attestation of the acceptability defines the acceptability, assuring it through to the next stage of the lifecycle. This progression is illustrated in Figure 4 identifying the four intermediate barriers and the one transition barrier. The final area of concern is that there is no loss of integrity through supply, for this reason a check of the supplied product, supplier personnel standards and supplier process is also carried out, giving a sixth attestation.

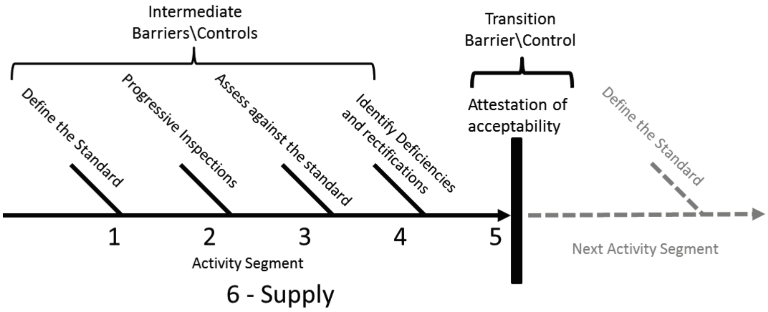


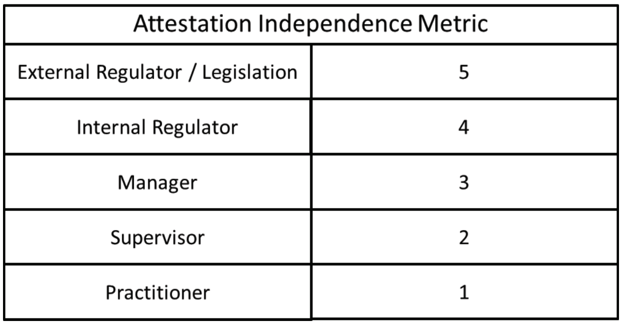
Figure 4: The breakdown of the steps required for certification during the lifecycle of an item. These steps are repeatable through every phase of the lifecycle certification process.

These six test points can be repeatedly applied to all stages requiring assurance. Directly relating to the adapted PBP Bow-Tie; these test points are applicable to product, behavior (people) and process within the lifecycle activities of design, production and maintenance. For instance, during design a standard is required to be defined (Barrier 1) for the product, the person performing the design and the process the person is utilizing. The same requirement applies for production and maintenance. From this a series of test points can be developed, where there are six test points for each technical lifecycle activity in each integrity line. This makes 57 (54 as discussed, with three additional Behavioral Integrity test points to characterize human factor management systems within Design, Production and Maintenance) test points to assess likelihood reduction barriers in a Technical Airworthiness Framework (left hand side of the PBP bow-tie).

2.3. Independence as a Metric

James Reason [30-32] establishes the significance of the work environment, management, and organization in influencing the decisions and actions of personnel. Reason highlights that these factors introduce latent conditions for failures of the system. The decision making of personnel involved in technical airworthiness should be made with a primacy on safety; however, decisions made from within the regulated-organization are influenced by a desire for performance, affordability and time. This is the motivation for regulatory organizations that are free from management pressures, and as such can instigate rules that focus on safety. Although one could argue that the public and government serve as the ultimate overarching level of organization influencing the decisions made by the regulator.

There is an implicit and required tension between the regulator and the regulated community [33, 34], driven by these conflicting organizational objectives. The regulator prescribes the bounds in which decisions are made, and it is the role of the regulated-organization to identify the most economical, best functioning and quickest solution that provides the required output within those bounds. However, with organizations and management identifying these efficiencies, they can inadvertently introduce the latent conditions for failure, or Reason's Swiss cheese holes. By discerning the organizational level at which decisions are made it is possible to understand the safety focus. For example, decisions relating to safety made by the person conducting the activity are susceptible to management and organizational pressures. Contrast this with a regulator making a safety decision about an activity and the management and organizational influences are removed. In this paper the PBP Bow-Tie derived test points are given a fidelity measurement based on the independence with which the attestation is made. Derived from this it is possible to score the representation of each Military technical airworthiness framework within the PBP Bow-Tie. Discerning the areas in which there is regulator interaction. The scaling of the independence measure can be applied to the different levels of a Military Technical Airworthiness model, as illustrated in Figure 5. It is worth noting that the scale of the measurement does not reflect weighting, it is purely representative of the different levels.



Attestation Independence Metric	
External Regulator / Legislation	5
Internal Regulator	4
Manager	3
Supervisor	2
Practitioner	1

Figure 5: The fidelity metric for the PBP Bow-Tie assessment. Independence within airworthiness correlates to remoteness from management and organizational influences. This allows for comparative assessment of attestations, it does not qualify the attestation as good.

By scoring each Test Point of the PBP Bow-Tie model through this measurement, it is easy to identify the areas in which the regulator interacts with the regulated community (a score greater than three). This does not identify that there is a requirement for the regulator to make all attestations. Due to the characterization of behavioral integrity in the PBP bow-tie there is a required standard set for the organization or person making the attestation. This means that the most suitable person, based on those required standards, may have low independence from the work. However, by characterizing the framework by independence, the differences and subtleties of the regulatory framework are identified. Drawing particular attention to interaction of the regulator with the regulated communities, where scores greater than three indicate regulatory or legislative oversight.

3. The PBP Bow-Tie Assessments and Visualizations

The PBP Bow-Tie assessment provides a series of scores based on the independence of the attestation and a brief explanation for that score within a table. To enhance the value of the captured data, and provide ability for comparative assessment, a unique data visualization was prepared utilizing CIRCOS [35], a tool developed for genome visualization but applicable to any tabular data representation. The assessment and visualizations were prepared for European Aviation Safety Agency (EASA) and the four Military Technical Airworthiness frameworks (US Army, US Navy, UK MAA and the ADF) and some initial, qualitative analysis of the five systems is given. With the exception of the UK MAA and EASA frameworks, each Military Technical Airworthiness framework was assessed based on published procedures and data collected from interviews with key personnel. The ADF, US Army and US Navy PBP Bow-Tie Analysis was conducted with input from the respective technical airworthiness bodies.

3.1. Circular Histogram Explanation

It must be stated that the PBP Bow-Tie captures information that allows for learning and comparison. An MAA can use a PBP Bow-Tie assessment to identify areas of their Technical Airworthiness Framework, which are deficient or require further investment, for varying levels and phases of the technical lifecycle. The PBP Bow-Tie can also be used to compare assessments of different Technical Airworthiness Framework, thus, providing a tool for aiding international harmonization and recognition between MAAs.

If the PBP Bow-Tie is utilized as part of a recognition agreement, each MAA would utilize it to compare their respective systems. In this instance, since there is no recognition agreement, the paper will compare the Military Technical Airworthiness Frameworks to the EASA technical regulatory framework, understanding that there are differences between the application in oversight and safety of aviation. However, once the full suite of militarized EASA regulation documents are published (in this assessment all aspects are covered except for approved design standards), there will only be differences relating to Military specifics; like operational risk acceptance and carriage of explosive ordnance, that distinguish the European Civil and Military Airworthiness document application. The PBP Bow-Tie independence scoring for each test point has been displayed as a circular histogram. The histogram illustrates the test points and independence scores for the attestations. The circular histogram representation for the EASA assessment is shown in Figure 6.

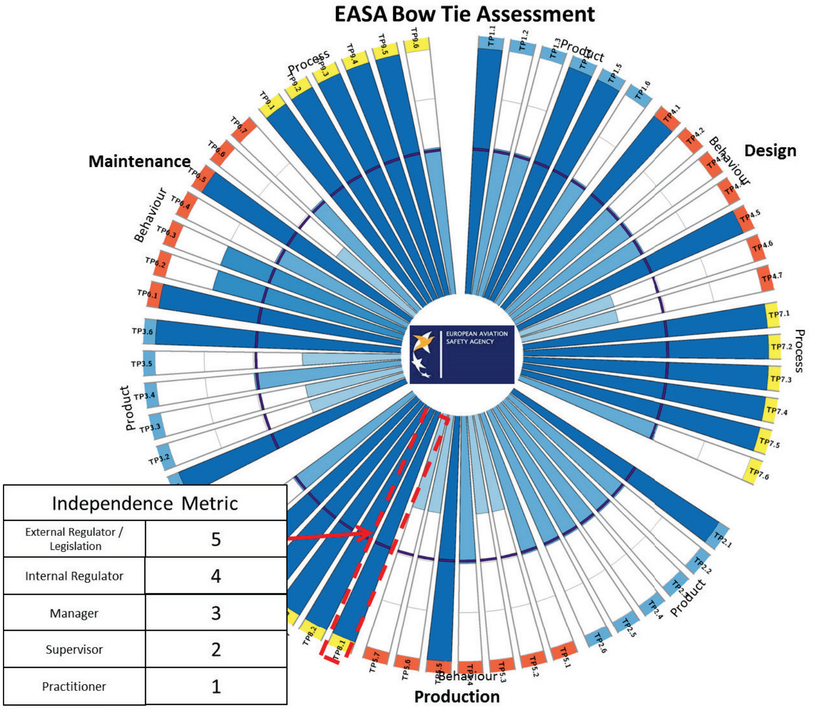


Figure 6: The EASA PBP Bow-Tie Assessment circular histogram used for visual comparison showing the relationship between the radial length of the test point score and the level of independence of the attestation. TP 8.1 (highlighted) shows that the Production process standard is set and attested to by an External Regulator, in this instance it is EASA part 21 subpart G for production.

The visualization in Figure 6 is grouped by phase of the technical lifecycle (i.e., Design-Production-Maintenance (DPM)). The test points within each phase are grouped based on the different mechanism through which integrity is being assured, i.e., Product (blue), Behavior (red) and Process (yellow). A measure of independence is then made for test point (refer Figure 5), the value of which is visualized by the length and shading of the radial. The higher the degree of independence for a test point the longer and darker the radial on the histogram. For example, test point 8.1 (TP8.1) highlighted in Figure 6, relates to standards for production processes and is captured through the requirements of the Production Exposition for Part 21 subpart G approval. An external regulator or legislator makes this attestation, the highest level of independence; hence the radial is dark blue and equal to a score of five.

Referring to Figure 6, it appears that EASA applies greater regulatory oversight in relation to process integrity (yellow), through exposition approvals, than product or behavioral integrity. The histogram plots can be visually grouped by integrity line (defined in §1.1) or by different phases of the technical lifecycle (defined in §2.1). The two alternate representations allow for different areas of focus in a comparison between assessments. The assessment illustrated in Figure 6 is grouped based on activity. Grouping by activity allows for identification of regulatory focus, is there a regulatory focus on design, production or maintenance for assuring technical integrity. Alternatively, the assessment can be visualized by grouping by integrity line. This approach qualifies the regulatory focus of the airworthiness authority. A comparison plot for EASA and the US Army grouped by integrity lines is shown in Figure 7. When conducting a comparison it is useful to examine the results of the assessment using both visualization groupings.

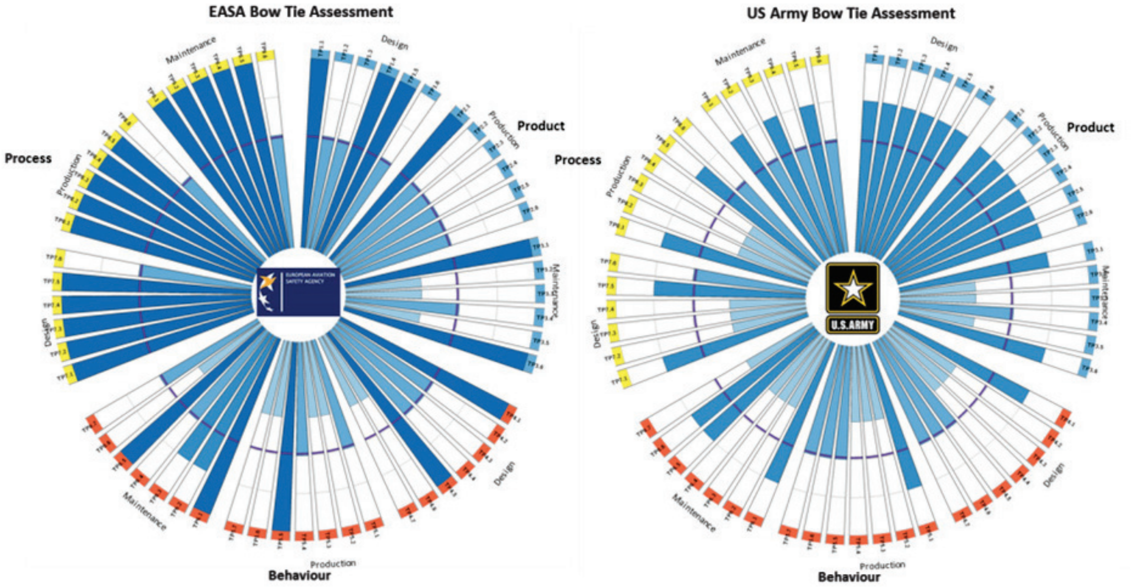


Figure 7: This figure compares the EASA PBP bow-tie assessment to the US Army assessment. Of note, this illustration has the histogram grouped by integrity line (clockwise - all Product then all Behavior and finally all Process), with the activities represented for each integrity line in order of the phases of the technical lifecycle (DPM). The strong EASA focus on Process Integrity is immediately visible; likewise the US Army's strong focus on independence in Product integrity is easily identified.

3.2. Comparison of Histograms – Grouped by Integrity Line

Assessment by integrity line provides for reconciliation of the different applications. For instance, it is possible to identify those regulatory organizations that have derived their implementations from the two pre-eminent civil aviation authorities; the European Aviation Safety Agency (EASA) and the Federal Aviation Authority (FAA). EASA have implemented robust organizational approval mechanisms, requiring detailed expositions that characterize the design, production and maintenance management systems, giving a strong focus on process integrity (yellow). While the FAA have traditionally focused on controlling product integrity (blue); having stringent requirements for the design, production and maintenance of the physical product. Figure 8 is a composition of the five airworthiness frameworks assessments grouped by integrity line. It shows EASA located central (a), the EASA derived frameworks are to the left; the UK MAA and ADF ((b) and (c) respectively) and the FAA derived airworthiness frameworks; the United States Army and United States Navy are on the right ((d) and (e) respectively).

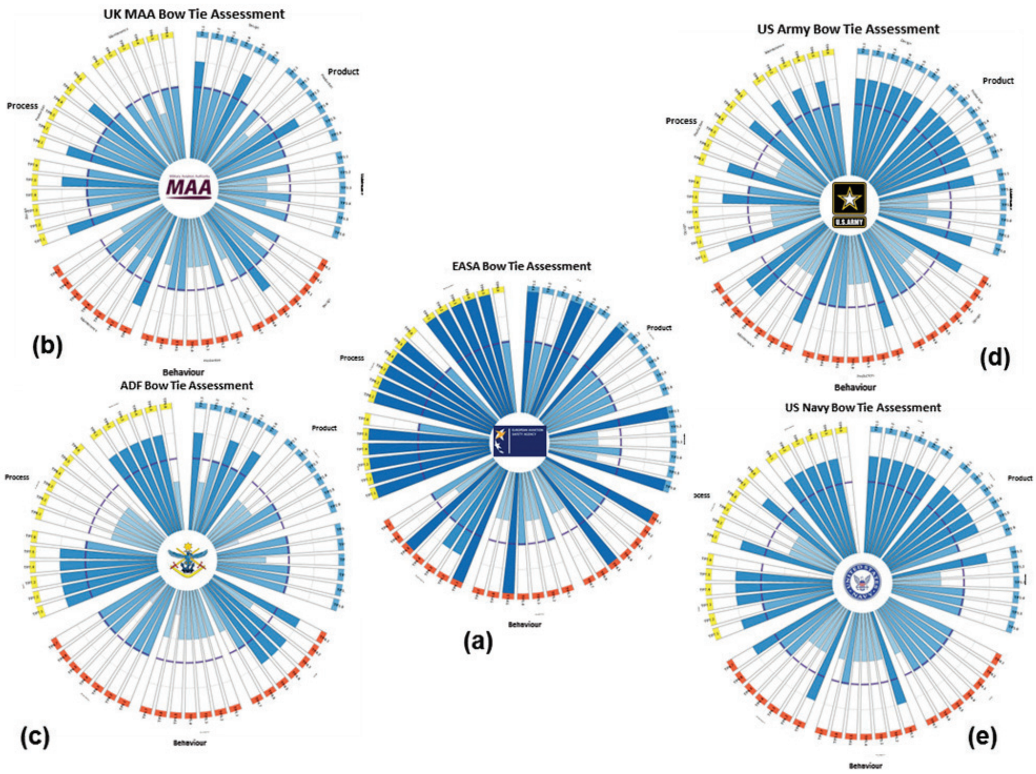


Figure 8: These five histograms are utilised for comparison, the purple ring indicates a score of three. (a) is the EASA plot, (b) is the UK MAA, (c) is the ADF, (d) is the US Army and (e) is the US Navy. These plots are grouped by integrity line and demonstrate primary areas of regulatory focus.

The histograms readily identify areas of difference through comparison of the length and subsequent shade of the radial test point scores. It is immediately apparent that EASA (Figure 8 (a)), being empowered through legislation and external to those organizations they oversight, score highly for independence of attestation for many test points. EASA score particularly well for control of process integrity (yellow); this is derived from their organizational approval process. Comparing EASA to the UK MAA (Figure 8 (b)) it is seen that the UK MAA have a more holistic airworthiness system, showing balance with a smaller, but still apparent focus on process integrity. Of note, the UK MAA does not yet apply the same regulations on their Military organizations as they do their civilian contracted agencies (this is not drawn out in this figure but will form the basis of some future work). Similarly the ADF (Figure 8 (c)) enforces strict requirements for Design and Maintenance process integrity, with their regulator, DGTA-ADF sitting internal to Defence, they score many fours in this area. However, it is immediately identifiable that they have poor regulatory control of Production, scoring low on most related test points. The US Army (Figure 8 (d)) has recurring internal regulator involvement, but immediately characterized is their predominant control of product integrity. Similarly, the US Navy (Figure 8 (e)) control product integrity through internal regulator involvement, characterized by scores of four through Design and Production integrity.

3.3. Comparison of Histograms – Grouped by Phase of the Technical Lifecycle

The other way of visually grouping the output from the PDP Bow-Tie assessment is by phase of the technical lifecycle (as defined in §2.1). This method of analysis allows for comparison of relative regulatory control of the activities undertaken within each phase (e.g., design, production and maintenance), enabling conclusions regarding the relative strengths and weaknesses of the regulatory frameworks. Figure 9 illustrates the same five regulatory framework assessments, however the test points are radially grouped by the activity phase; with Design (12 to 4 o'clock), Production (4 till 7 o'clock) and Maintenance (7 till 12 o'clock) showing comparative focus. The histograms are positioned the same; EASA (a), UK MAA (b), ADF (c), US Army (d) and US Navy (e).

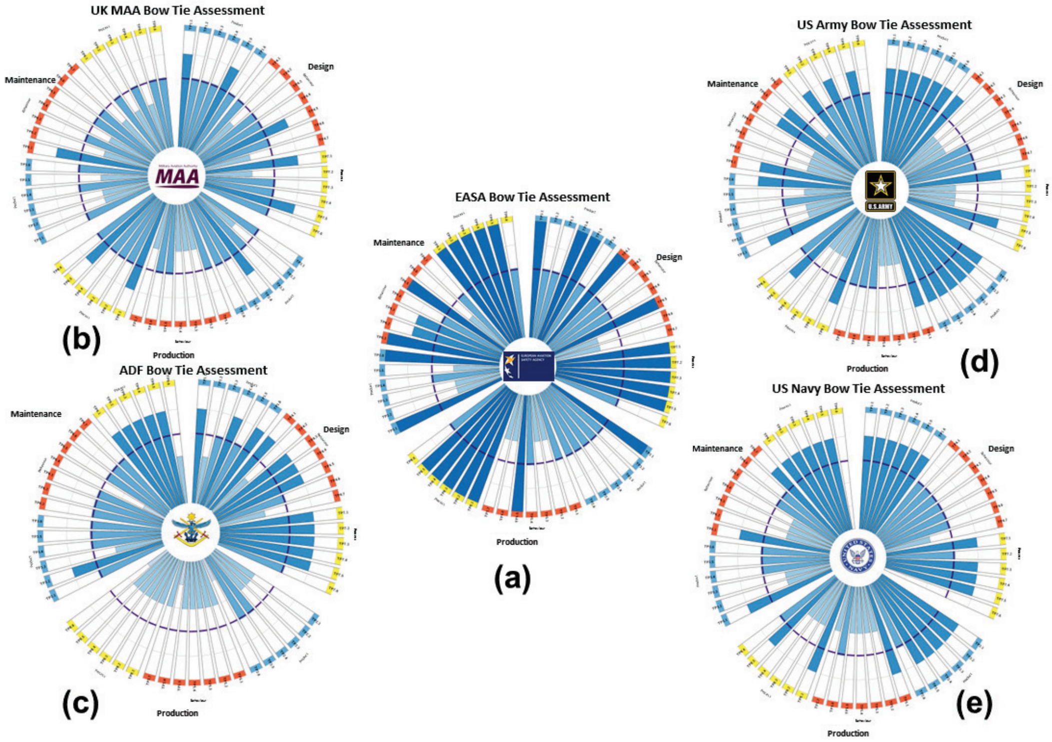


Figure 9: These five technical airworthiness histograms are utilised for comparison. (a) is the EASA plot, (b) is the UK MAA, (c) is the ADF, (d) is the US Army and (e) is the US Navy. These plots are grouped by activity segment demonstrating relative strengths of the airworthiness organization.

3.3.1. Visual Analysis

This analysis, while utilizing the same data sets, provides a method for identification of the regulatory areas of focus within the regulatory framework. For instance, EASA (Figure 9 (a)) are shown to have slightly more interaction with Design and Maintenance than on Production. The UK MAA (Figure 9 (b)) interact more heavily with Design, which is easily identifiable as the area of most regulatory control for the ADF (Figure 9 (c)), with the ADF Production oversight an immediately identifiable regulatory weakness. With the US Army (Figure 9 (d)), it is apparent that they rely on product integrity for Design and Production, having less independence with behavioral and process integrity within those two activities. Maintenance has more regulator interaction for attestations. Similarly, the US Navy (Figure 9 (e)) regulator interaction is product focused for Design and Production; however, they have independent regulator attestations within their framework for design and maintenance management processes.

4. Conclusion and Future Work

This paper has presented a novel application of the Bow-Tie model for assessing technical regulatory frameworks. The same system and fundamental principles are transferable beyond the aviation regulatory domain, and as discussed in the paper, can be evolved to address other regulatory frameworks, not just technical airworthiness. The novel adaptation provides a fundamental axiom for developing confidence in an attestation of acceptability. This axiom is applied within the technical item lifecycle model for Design, Production and Maintenance. Sets of test points were defined that capture the breadth of activities under each phase of the lifecycle. A measure of independence in the attestation was used to score the frameworks and utilized to identify the Technical Regulatory interaction. Independence is an important and often implicit feature of a sound regulatory framework. Where, in the interest of safety, organizations are required to comply with a set of regulations or rules developed by an independent body, completely removed from the work of the regulated organization. This is apparent with government-enforced airworthiness, work health and safety, financial and food hygiene regulation for instance.

The scoring of the five technical airworthiness frameworks using the independence metric facilitated the identification of differences between the regulatory frameworks. This style of analysis can be further refined when a comparison is required between two frameworks, allowing for greater detail in identification of the implementation differences, drawing out the motivations and importance to these deltas.

This paper was aimed at proving the preliminary success of this methodology for providing a visual comparison that enables identification of areas requiring further examination. The assessment framework and accompanying visualization provides a platform for Military Airworthiness Authorities to analyze areas of deficiency or create a platform for harmonization or recognition with other Authorities. This may be further facilitated by the recognition platforms created within the EDA and NATO. The flexibility of the tool is illustrated by its application to civil airworthiness regulator. In addition to utilizing the framework as a comparison tool it can also be utilized as a learning tool.

The framework developed in this paper will be extended to include analysis of the differences for regulatory oversight within Defense design, production and maintenance organizations and Civilian contracted design, production and maintenance organizations. There are many military regulatory authorities that do not apply the same regulatory oversight to these organizations. performing the same role often on the same technical items, including aircraft. Further, there are Military Airworthiness Authorities that have more regulatory oversight of design, production and maintenance during initial aircraft certification than they do during continuing airworthiness. These subtleties can be extracted utilizing different visual groupings of the circular histogram plots.

In summary, this paper has developed a novel application of the Bow-Tie model that separates technical integrity into its constituent parts; product, behavior and process integrity. Test points were then developed based on the fundamental axiom of an attestation. A metric for that provides fidelity to the assessment based on the independence of those attestations was proposed. The independence metric enabled identification of regulator interaction within the technical item lifecycle as well as a platform for comparison of technical regulatory systems. Further, a unique circular histogram visualization of the PBP Bow-Tie assessment provides a mechanism for easy comparison between different regulatory applications. The visualization provides a simple yet powerful method for rapid identification of regulatory framework differences. This allows for a common understanding between technical airworthiness authorities. Further, the assessment does not breach any privacy concerns for Militaries and their technical airworthiness frameworks, allowing for a global interaction platform that can be facilitated for non-allied countries.

5. Copyright

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References

[1] International Civil Aviation Organisation (ICAO). *DOC 9734 - Safety Oversight Manual*: International Civil Aviation Organisation (ICAO), 2006.
[2] International Civil Aviation Organisation (ICAO). *DOC 7300/9 - International Convention for Civil Aviation - more commonly known as The Chicago Convention*: International Civil Aviation Organisation (ICAO), 2006.
[3] European Defence Agency. "European Military Airworthiness Document - Recognition (EMAD-R)." 2013.
[4] Purton, L., Kourousis, K., and Clothier, R. "Military airworthiness management frameworks: a critical review." Proceedings of the 3rd International Symposium of Aircraft Airworthiness 21-23 November 2013, Procedia Engineering, published 2014.
[5] Department of Defence, "DI(G) OPS 02-2: Defence Aviation Safety Program," 2011
[6] Woodside. "Techical Integrity / Process Safety; what is it?," *Presentation to NOPSEMA forum by Woodside (Mary Hackett)*, February, 2008.
[7] Clifton A. Ericson, I. *Hazard Analysis Techniques for System Safety*: Wiley, 2005.
[8] Sklet, S. "Safety barriers: Definition, classification, and performance," *Journal of Loss Prevention in the Process Industries* Vol. 19, No. 5, 2006, pp. 494-506.
[9] Guldenmund, F., Hale, A., Goossens, L., Betten, J., and Duijm, N. J. "The development of an audit technique to assess the quality of safety barrier management," *Journal of Hazardous Materials* Vol. 130, No. 3, 2006, pp. 234-241.

[10] de Dianous, V., and Fiévez, C. "ARAMIS project: A more explicit demonstration of risk control through the use of bow–tie diagrams and the evaluation of safety barrier performance," *Journal of Hazardous Materials* Vol. 130, No. 3, 2006, pp. 220-233.

[11] Harms-Ringdahl, L. "Analysis of safety functions and barriers in accidents," *Safety Science* Vol. 47, No. 3, 2009, pp. 353-363.

[12] Hollnagel, E. *Barriers and Accident Prevention*: Ashgate Publishing Limited, 2004.

[13] Summers, A. E. "Introduction to layers of protection analysis," *Journal of Hazardous Materials* Vol. 104, No. 1–3, 2003, pp. 163-168.

[14] Rothschild, M. "Fault tree and layer of protection hybrid risk analysis," *Process Safety Progress* Vol. 23, No. 3, 2004, pp. 185-190.

[15] Markowski, A. S., and Kotynia, A. "“Bow-tie” model in layer of protection analysis," *Process Safety and Environmental Protection* Vol. 89, No. 4, 2011, pp. 205-213.

[16] Myers, P. M. "Layer of Protection Analysis – Quantifying human performance in initiating events and independent protection layers," *Journal of Loss Prevention in the Process Industries* Vol. 26, No. 3, 2013, pp. 534-546.

[17] Chevreau, F. R., Wybo, J. L., and Cauchois, D. "Organizing learning processes on risks by using the bow-tie representation," *Journal of Hazardous Materials* Vol. 130, No. 3, 2006, pp. 276-283.

[18] Duijm, N. J. "Safety-barrier diagrams as a safety management tool," *Reliability Engineering and System Safety* Vol. 94, No. 2, 2009, pp. 332-341.

[19] Mokhtari, K., Ren, J., Roberts, C., and Wang, J. "Application of a generic bow-tie based risk analysis framework on risk management of sea ports and offshore terminals," *Journal of Hazardous Materials* Vol. 192, No. 2, 2011, pp. 465-475.

[20] Lewis, S., and Smith, K. "Lessons learned from real world application of the bow-tie method." 2010, pp. 472-483.

[21] Ferdous, R., Khan, F., Sadiq, R., Amyotte, P., and Veitch, B. "Handling and updating uncertain information in bow-tie analysis," *Journal of Loss Prevention in the Process Industries* Vol. 25, No. 1, 2012, pp. 8-19.

[22] Ferdous, R., Khan, F., Sadiq, R., Amyotte, P., and Veitch, B. "Analyzing system safety and risks under uncertainty using a bow-tie diagram: An innovative approach," *Process Safety and Environmental Protection* Vol. 91, No. 1–2, 2013, pp. 1-18.

[23] Bale, E. A., and Edwards, D. W. "Technical Integrity–An Engineer's View," *Process Safety and Environmental Protection* Vol. 78, No. 5, 2000, pp. 355-361.

[24] Gifford, M. J., Gilbert, S. M., and Barnes, I. "The Use of Bow-tie Analysis in OME Safety Cases," *ESAS 03*, 2003.

[25] Couronneau, J. C., and Tripathi, A. "Implementation of the New Approach of Risk Analysis in France," *41st International Petroleum Conference*. Bratislava, 2003.

[26] Lewis, S., and Smith, K. "Lessons learned from real world application of the bow-tie method: Presentation only." 2010.

[27] Svenson, O. "The accident evolution and barrier function (AEB) model applied to incident analysis in the processing industries," *Risk Analysis* Vol. 11, No. 3, 1991, pp. 499-507.

[28] Collins, B., and Pitblado, R. "Barrier management for offshore safety," *Oil and Gas Journal* Vol. 110, No. 6, 2012, pp. 1-B34.

[29] Cardwell, G. "The application of the Four Essentials Bow Tie Diagram to enhance business success," *Total Quality Management & Business Excellence* Vol. 19, No. 1-2, 2008, pp. 37-45.

[30] Reason, J. *Managing the risks of organizational accidents*: Aldershot: Ashgate, 1997.

[31] Reason, J. "Education and debate: Human error: Models and management," *British Medical Journal* Vol. 320, No. 7237, 2000, pp. 768-70.

[32] Reason, J. *Human Error*: Cambridge University Press, 1990 (first published).
[33] Freiberg, A. *The Tools of Regulation*: The Federation Press, 2010.
[34] Australian National Audit Office (ANAO), "Administering Regulation: Better Practice Guide," 2007
[35] Krzywinski, M. I., Schein, J. E., Birol, I., Connors, J., Gascoyne, R., Horsman, D., Jones, S. J., and Marra, M. A. "Circos: An information aesthetic for comparative genomics," *Genome Research*, 2009.