A quantitative Safety Assessment Tool based on Aircraft Actual Navigation Performance

Markus Vogel, Christoph Thiel, & Hartmut Fricke
Chair of Air Transport Technology and Logistics
Technische Universität Dresden (TUD)
Dresden, Germany
vogel@ifl.tu-dresden.de; thiel@ifl.tu-dresden.de, fricke@ifl.tu-dresden.de

Abstract—**With this paper, Air Traffic Safety research at TU Dresden presents its ongoing effort to establish a safety metric for normative air traffic operations. First, current safety assessment methodology is analyzed. We then present our quantitative approach that focuses a technologically founded but objective view on total system safety by probabilistically assessing pair-wise aircraft interaction based on the discrepancy between intended and actual locations. Focusing the terminal area (TMA) around major airports, quantitative mathematical models for this discrepancy have been established through fine-grained radar data analysis. The safety assessment tool actively uses these actual navigation performance (ANP) values for adaptive parameterization. To show the practicability of our approach, segregated operations on parallel runways and the related planning rule for runway staggering are subjected to safety assessment, by means of both a geometric analysis of critical cases and safety assessment following our approach. The results indicate a relation between the presented approach and the reasoning that led to the planning rule but also point out the essential differences. Finally, outlook on future work is given: the safety assessment tool shall be utilized to analyze current controller strategies at the TMA in high spatial and temporal detail, gaining the knowledge necessary to model future systems and procedures.**

Keywords: operational air traffic safety; quantitative safety assessment; safety methodology; collision risk; human performance modelling

I. INTRODUCTION

The ICAO Safety Management Manual [1] defines safety as the "state [at] which the possibility of harm to persons or of property damage is reduced to, and maintained at or below, an acceptable level" and defines the SHEL model for the air traffic system as a human-machine system consisting of **s**oftware (procedures, etc.), **h**ardware (technology), (working) **e**nvironment, and **l**ifeware (humans). To quantify safety (the absence of unsafe conditions following the definition above) one must resort to safety indicators, e.g. incidents or fatal accidents. This leads to the definition of a system's level of safety (LoS) as its observed safety. To ensure and maintain safe operations, regulatory and legislating bodies shall define a target level of safety (TLS) for all safety-critical systems.

Various TLS for different aspects of air traffic have been defined and published in ICAO and ESARR documents (see tab. 1) specifying the highest acceptable rate of safety occurrences expressed in relative frequencies. It shall be noted that the TLS definitions use different units: they are either related to flight hours, flight segments, or typical operations. The numeric values imply that safety occurrences in aviation are expected to be excessively rare. For current systems and procedures, this means that low traffic volumes and brief observation times impede observation of the LoS. For future, currently non-existent systems, e.g. decision support tools (DST) or adopted procedures to accommodate rising and/or changed traffic demands, safety indicators are hard to define. Most often, the LoS can only be quantified through probabilistic estimation. Consequently, the authors see a need for a quantitative safety metric that addresses TLS.

TABLE I. LIST OF COMMONLY AGREED TARGET LEVELS OF SAFETY

Domain	Value, unit, threat	Definition
en-route operation	$5.0 \cdot 10^{-9}$ per flight hour fatal mid-air collision	ICAO ANNEX 10 [2]
surface operation	$1.0 \cdot 10^{-8}$ per operation fatal/hull-loss accident	ICAO ASMGCS [3]
approach operation	$1.0 \cdot 10^{-7}$ per approach fatal obstacle collision	ICAO PANS-OPS [4]
air traffic management	$1.55 \cdot 10^{-8}$ per flight hour direct controller contribution to reduced safety	ESARR4 [5]

While qualitative and probabilistic safety assessment methodologies have been prevailing in the past [5], quantitative data, adequate processing and description methods, and capable computing hardware are widely available today. This allows for more complex examinations of safety indicators and the design of qualitative safety metrics.

The research focuses the terminal area (TMA) around major airports. This sector is of special interest because traffic demand is high, driving sector load and spatial density of aircrafts. Current safety regulations require separation minima to be upheld, while air traffic procedures require substantial ground guidance (controller planning and communication), rendering the TMA a bottleneck for the entire air traffic system. As the current development shows, major changes in both procedures (e.g. 4D approach trajectories) and technology (e.g. GPS navigation) drive changes in the system. Changes in the air traffic system must be neutral or better beneficial to the overall system safety. With final approach and take-off being the most critical flight phases and a proven dependency between midair collision probability and traffic density, safety in the TMA is always at stake.

The SHEL model illustrates well the multiplicity of potential causes for operational errors in the air traffic system. As an example, consider the diversity of human error: faults (*wrong thinking*), mistakes (*wrong acting*), lapses (*wrong attention*) and also violations (*wrong attitude*) are quite contradictory concepts. Depending on the consequences, the typical result of all errors is reduced safety. Air traffic safety research at TU Dresden is ongoing since several years [11, 13] and focuses technological, operational and cognitive safety hazards, i.e. SHEL hardware, software and lifeware. This paper presents the ongoing effort to quantitatively assess the overall system safety without inspecting individual system components. Further work shall combine the safety assessment tool with knowledge about procedures (regulations, task analyses) and human factors (cognitive effects, e.g. decision-making) to quantify the safety impact of the identified subsystems by means of an inhomogeneous agent-based simulation.

II. SAFETY ASSESSMENT TOOL

A. Methodological Foundation

1) Probabilistic Safety Assessment: A substantial number of quantitative safety assessment techniques for air traffic have been developed and validated in practical applications [5]. Probabilistic approaches are predominant, building up on well established safety assessment techniques like fault and event tree analysis (FTA, ETA), probabilistic safety analysis (PSA), reliability analysis, failure mode and effects analysis (FMEA), and probabilistic cognitive models of human error. All these approaches hierarchically decompose the air traffic system and assign likelihoods of undesired behavior to the "atomic" elements of decomposition. The level of detail is commonly determined by some type of "cost" function. Total system safety is cumulated from the tree-structured safety model, resulting in an overall probability for system failure.

While practically relevant and applicable, these techniques do not address safety at normative operations but stress component failures in a binary (operational/faulty) fashion. In addition, substantial safety expertise and knowledge of the system under examination is needed for a valid assessment. As a consequence, the obtained LoS depends on the level of detail and the amount and quality of assumptions in the underlying model.

2) Quantitative Safety Assessment: Air traffic safety research at TU Dresden follows a related but essentially different approach. By coupling quantitative models to a slim probabilistic safety assessment, system analysis and safety assessment are separated. There are two major benefits: (1) openness to alternate safety metrics which can be applied to the quantitative models, (2) the ability to assess safety for existing and simulated systems alike. Both meet our research hypotheses: the authors question the sufficiency of one single safety metric for all cases and disciplines (consider technical system failure vs. human error) and deem quantitative models incorporating the findings in aviation and human factors to be superior to established safety models by making the achieved level of detail explicit (in structure and quantity). In the case of existing systems, measured flight track data is used as input for safety assessment, resulting in the highest possible level of detail.

The obvious approach for safety assessment using aircraft locations follows the well established separation concept. Time/distance- and density-based safety metrics are widespread [5, 6-8] but lack fidelity [9]. For this reason, probabilistic approaches quantifying the interaction of aircraft pairs have been investigated by numerous researchers over the past twenty years [10-12]. Overall, two classes of probabilistic functions have been addressed: location probability and conflict probes. The former addresses the discrepancy between intended and true aircraft location in dependence of various factors, e.g. steering accuracy, navigation tolerance, and weather influence. Location probability functions are of descriptive nature. The latter represent functions extending lobes into the considered aircrafts' intended trajectory. Evaluating these functions leads to safety zones weighted with criticality (time to go for evasive action such as applied in the standardized TCAS logic [2, 14]). Thus, probabilistic conflict probes are of predictive nature. The primary applications have been collision avoidance and conflict detection (e.g. TCAS, STCA).

B. Previous Work

Driven by the wide availability of radar and simulation data, previous work at TU Dresden applied location probability functions to assess safety [11, 13]. Initially, tracking inaccuracies along flight paths were modeled with tubular location probability functions aiming to support the airspace layout process with a local collision-based safety metric [11]. The concept was later extended to three-dimensional location probability functions to evaluate explicitly the collision risk at a given time and location, thereby adding temporal resolution to the local resolution. This resulted in a software package called *Safety Korrelator*, a Java-based tool for collision risk assessment.

Within the *INTEGRA* research project, Eurocontrol implemented a similar metric [14]. With the aim of developing a safety metric that facilitates comparisons between different traffic situations, *propensity*, defined as the "likelihood of a safety significant event occurring during normal operations", was conceived. Propensity quantifies pair wise aircraft interaction in a probabilistic fashion, taking into account the normative capabilities of the air traffic control system in use. Although these capabilities are generally user-definable, [14] provides three sets of "reasonable default values" for navigational variances depending on the mode of en-route traffic control (manual, 3D, and 4D). These variances are weighted with several modifiers to reflect influences by severe weather, traffic complexity, advanced navigation aids, and task-load induced changes in operator performance.

C. *Safety Assessment Concept*

Building up on previous work at TU Dresden and Eurocontrol, the core of our safety assessment concept is the evaluation of the midair collision probability that arises from aircraft location inaccuracies. The intended locations are the quantitative input into safety assessment. The system-wide collision probability is evaluated through numeric integration of all aircraft location probability density functions. Mathematically, this is less elegant (and less efficient) than the possible symbolic integration – but scientifically interesting, because spatial resolution is achieved, allowing visualization and hotspot analyses of the results.

Location inaccuracies are modeled in form of three-dimensional normal distributions, following numerous practical observations [16]. The important novelty of our approach is the integrated adaptive parameterization with actual navigation performance values (ANP) obtained from radar data analyses at major airports in Europe [17, 18]. The respective mathematical analyses confirm that tracking deviations are indeed normally distributed and quantify navigation tolerances. For selected critical flight phases in the TMA, e.g. final approach and take-off, precise mathematical dependencies were derived. For other flight phases in the TMA, e.g. holding and transitions, static ANP values were determined. The quantitative results summarize all tracking deviations including flight technical, navigational and human error as well as weather influence.

The concept focuses a slim, technologically founded, and meaningful safety metric. In fact, the influence of human error on the ANP values actually contradicts this principle. Similarly, the weighting factors in *INTEGRA* add a substantial number of degrees of freedom to the safety metric, altering the level of detail and leaving unnecessary room for assumptions. (e.g. the "use of advanced tools" weighting factor defaults to either 1.0 or 0.6 [14]). While weather influences, flight technical, and navigational errors are rightfully included in the safety assessment concept, the authors believe that the influence of human factors should be limited to the lowest possible extent in order to shift the modeling from safety assessment to the underlying quantitative model. The ANP values used for safety assessment fully exclude controller influence (while maintaining pilot influence) due to the fine-grained analysis of track data, which isolated flight segments in a way that controller intervention was out of the question. Consequently, alternate safety assessment approaches for safety assessment addressing the issue of human factors can still be incorporated. The authors rightfully acknowledge human factors influenced complexity metrics like *Dynamic Density* [8] with the note that the transfer function between controller task load and air traffic system safety is yet to be identified [9].

D. *Software Implementation*

With regard to code flexibility and future integration of related approaches and tools in the light of changing research objectives, the Java programming language was chosen. Fig. 1 depicts the package structure and names core classes.

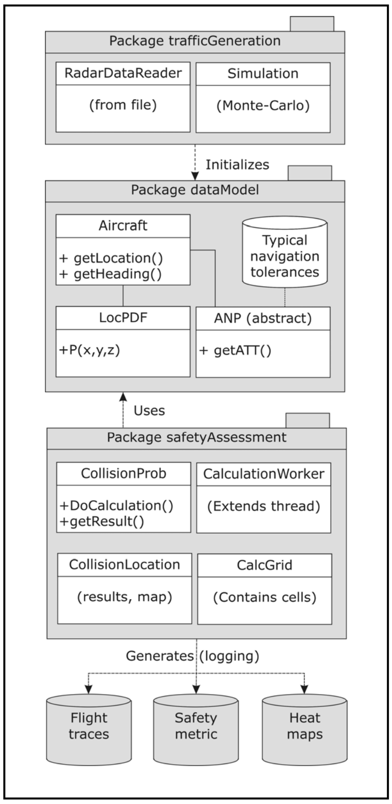

Figure 1. Safety Assessment Tool package structure *(overview)*

The *safety assessment* tool itself is packaged independently but uses the *data model* representing the traffic scenario (airspace plus aircraft locations over time), thus serving as an intermediate information structure. The contained quantitative information is either real flight track data (e.g. from radar analyses), simulated flight track data (e.g. from real-time simulations with humans in the loop), or extrapolated track data (e.g. from computer simulations). Our software abstracts the various data sources with the *traffic generation* package, containing file readers or interfaces to externally implemented simulations. Database integration for input data is planned for future versions, as extensive simulations of greater complexity are intended. Persistence of output data is currently reached through logging.

Though runtime was considerably lowered in comparison to *Safety Korrelator*, the numeric integration of the collision probability remains computationally demanding. Various optimizations, including multi-stage processing, look-up tables for trigonometric functions, and fine-tuning of the calculation algorithm are accountable for the majority of speedup, while parallelization of the core calculation yielded only a minor speedup of roughly 1.45 (on dual-core commodity personal computers).

E. Reference Results

As a reference, levels of location and collision probability were calculated and tested on their Gaussian distribution. The case of two aircrafts on crossing flights paths was examined as well to gain further insight. A mathematical theorem, that the convolution of two Gaussian functions is again a Gaussian proves to be applicable to this case (location probability functions are Gaussians and the variation of location matches the definition of convolution). As expected from commonly agreed-on TLS values, collision probabilities approach zero even at considerably unsafe aircraft separation values. Therefore, logarithmic scales are used in the diagrams showing collision probabilities.

Next, a simple sensitivity analysis to the aircraft's track keeping performance was undertaken. Although in reality, altitude measurements surpass location measurements in accuracy, both cross track (XTT) and vertical track (VTT) tolerances were jointly varied between 0 and 200 m while maintaining a constant along track tolerance (ATT) of 300 m to model increasing tracking performance versus constant inaccuracies in lateral positioning (e.g. self-separation). To capture severe reactions of the safety metric, aircrafts were positioned in ANP-proximity (1) in line on the same track (300 m separation) and (2) in parallel (100 m separation). The results (shown in fig. 2) illustrate the nonlinearity of collision probability: Increased track keeping capability (low XTT/VTT) lowers the collision probability of laterally separated aircraft (parallel tracks, dashed red plot) but increases the collision probability of longitudinally separated aircraft (same track, solid blue plot).

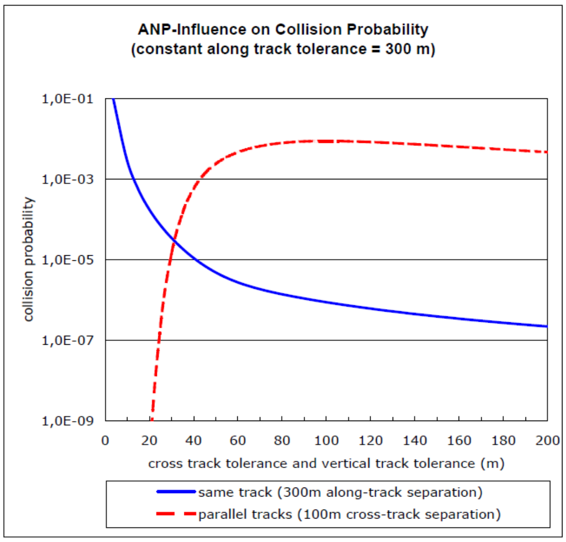

Figure 2. Influence of track keeping capability on collision probability

III. Segregated Operations on Parallel Instrument Runways

A. Introduction

As a proof-of-concept, simultaneous operations on parallel or near-parallel instrument runways (SOIR, [19]), were selected for further analysis. SOIR, especially segregated operations (mode 4), is of particular interest because the father document, ICAO Annex 14 [20] gives detailed information about requirements in airport layout and procedures, yet does not reveal the underlying scientific or empirical base. The narrow airspace in focus and the high detail in the requirements permit a straightforward construction of scenarios.

Distinct feature of SOIR is its rule about runway spacing, allowing a reduction down to 760 m for dependent or segregated parallel operations (compared to 1035 m for independent parallel operations). For segregated operations, i.e. dedicating one runway for landings and one runway for take-offs, the spacing varies as runways thresholds are staggered relative to each other, following the so-called 1/5-rule: Separation "may be decreased by 30 m for each 150 m that the arrival runway is staggered towards the arriving aircraft, to a minimum of 300 m" ([19] pp. 4-1) and must be increased vice-versa (see fig. 3 for illustration).

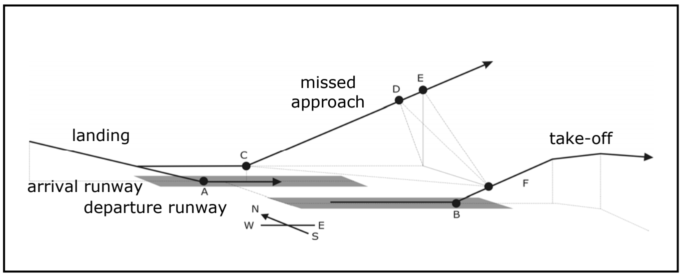

Figure 3. SOIR scenario with points of interest for minimal distances

Asking for the foundation behind this simple-looking linear dependency, an exemplary safety analysis using our safety assessment tool was undertaken. Considering the maturity of the rule, the first hypothesis is that a separation-based approach determined the dependency. Following the idea of safety targets in aviation (TLS), the second hypothesis follows the conjecture that a LoS in the magnitude between en-route operations and precision approach (10^{-9}-10^{-7} per operation) should be observable at segregated runways.

To get some methodological insight, both an analytic and a simulative analysis were performed. The analytic approach entails identifying safety-critical cases first and then computing safety while the simulative approach entails generating traffic scenarios first, then assessing safety, and finally interpreting the results.

B. Analytic Approach

1) Identification of Critical Cases: Although obstacle collisions are clearly the major hazard during final approach, the following analyses focus collision probabilities of airborne vehicles. The case of stationary threats is covered with this approach as well: obstacles can easily be modeled as stationary conflict partners with no inacurracy in location. Three basic types of operation were extracted from [19]: (1) successful landings, (2) missed approaches initiated at the minimum descent altitude (MDA or decision height, DH) and (3) departures (see fig. 3). Touch-and-go operations were considered as well, but discarded because they do not qualify as standard operating procedures, justifying the assumption of an influence on the 1/5-rule's design.

Following the well-established separation concept, critical cases are identified through geometric analysis. In order to analytically calculate critical distances, certain parameters (touch-down and take-off locations, the DH, go-around and take-off gradients) are assumed to be fixed. In particular, the nominal touch-down and take-off zones (TDZ, TOZ, [4]) are reduced to the fixed points A and B (see fig. 3). The north runway is designated for arrivals from the west, approaching with a 3° glide slope. If the approach is aborted at the DH of 200 ft, the missed approach path, an 800m horizontal section followed by a 10° incline, is taken [4]. The south runway is designated for departing aircraft (10° climb angle). The departure track diverts 30° from the missed-approach path after a brief straight-out climb phase according to [4, 19].

Without considering the following aircraft (let arriving and departing aircraft be sufficiently separated within), the critical distance for landings is easily identified as the distance between the points A and B. The critical case for missed approaches is not as easily identified. Due to identical climb angles, the missed approach path parallels the straight-out departure section. Thus, the critical distance equals the Euclidian (slant) distance between the flight segments (D-F in fig. 3). The cases of horizontal (C-F) and vertical (E-F) line-ups are equally considered with reference to the nonlinearities described in chapter II.E.

2) Critical Distances: Fig. 4 shows the calculated distances for the identified critical cases in dependence on runway staggering (the runway offset being charted at the lower x-axis and the resulting separation according to the 1/5 rule at the upper x-axis). Vertical separator lines indicate notable points for the 1/5 rule: below –2300m offset, runway spacing is constant at the defined minimum of 300 m; after that, the linear dependency applies; at 0 m offset, the runways threshold are aligned.

To get an understanding of the results, let us analyze the minimal distance of landing vs. departing flights first (A-B, dotted blue plot). The north, arrival, runway moves as the staggering is varied; hence, point B remains fixed whereas point A travels linearly following the 1/5 rule. The resulting change in distance leads to a hyperbolic dependency of distance to the runway offsets. Incidentally, the horizontal distance of the missed approach incline and the departure incline recreates the same conditions shifted by 50 m (C-F, solid black plot). In contrast, the minimal distance of the inclining path segments (D-F, dashed red plot) shows a different characteristic: the influences of runway offset and runway spacing counteract, spreading the hyperbolic curve. The contribution of both parameters to the minimal distance also shows in the bend occurring at –2300 m offset where runway spacing reaches the defined minimum of 300 m. For the vertical distance between the flight path segments (E-F, also dashed red), the difference is negligible due to the small relative angle of 10° (common approximation: $\cos(\alpha)\approx 1$ for small α values).

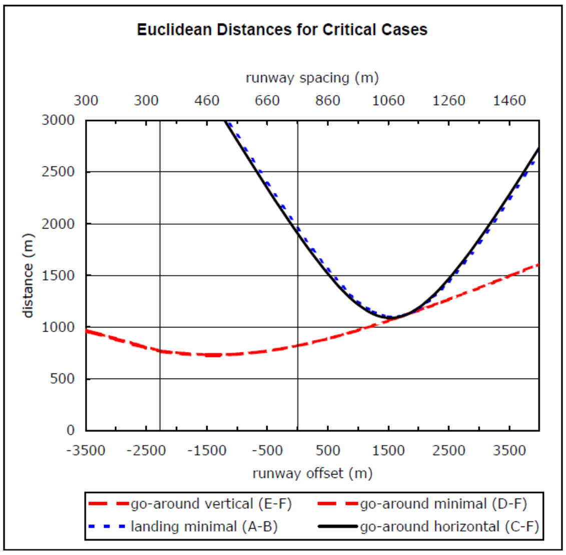

Figure 4. Minimial distances for critical cases in dependence of runway staggering

To conclude: the linear runway staggering dependency carries on in form of hyperbolic dependencies in critical distances. The critical distance for landing operations has a clear minimum (at 1600 m offset), while the critical distance for missed approaches has a weaker minimum (at –1500 m offset). Altogether, a separation-based reasoning behind the 1/5 rule does not become evident.

3) Collision Probabilities: Subsequently, a safety assessment was performed for the critical cases with arbitary navigation performance parameters (0.2 NM XTT and VTT, 0.3 NM ATT, derived from [13, 14]). The results are depicted in fig. 5, maintaining the x-axis and the color-coding of plots.

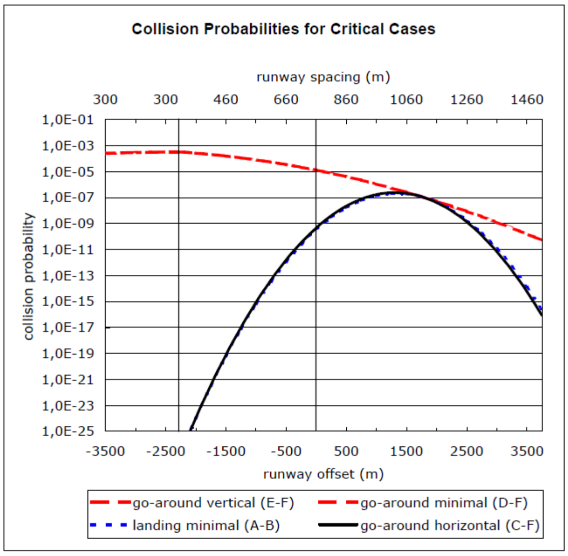

Figure 5. Collision probabilities for critical cases

Critical distances that appear to be equivalent in fig. 4 (A-B & C-F and D-F & E-F) were included in calculation, but the results do not reveal any notable differences in collision probabilities. A significant difference lies in the curves' shapes compared to fig. 3: due to the nonlinear transformation, the former hyperbolic shapes of distance become deformed Gaussians (of parabolic shape in logarithmic scale). Also, the linear segment of missed approach path separation at 300 m minimal runway spacing becomes considerably flattened (and retransformed into parabolic shape) while maintaining the characteristic bend indicating the change of dependencies.

A clear indication for the foundation of the 1/5 rule can again not be concluded. A look into the frequency of operations occurring at real airports may provide further insight: missed approaches are quite rare compared to successful landings and should not influence the design of specifications as much as nominal operations. Although the graph for landing operations does not allow any conclusions to be drawn, this approach is further deepened in the discussion of the simulation results, where comparable average values are available (meeting the definition of TLS in relation to flight hour or flight operation, see chapter I).

In retrospect, the authors find it important to note that the identification of critical cases and the calculation of critical distances and resulting collision probabilities are quite tedious and far from trivial. Even for the simple example presented here, important aspects had to be omitted: e.g. the fact that points C and D co-locate eventually and then wander into the horizontal flyover segment of the missed approach path, leading to another critical distance. Although a complete analysis is possible for this simplified SOIR example, more complex scenarios will be very demanding – the analytic approach will effectively lie beyond feasibility.

C. *Simulative Approach*

1) Traffic Scenarios: Highly abstracting real behavior, aircrafts were designed as point mass elements that follow a sequence of waypoints in a strictly linear fashion (no realistic turning behaviour). The self-contained software agents utilize some flight technical parameters (see tab. 2) that were extracted from the A320 flight manual [21] as a substitute for medium-sized aircraft (according to ICAO Wake Turbulence Category) predominating traffic at major European airports. Later modeling efforts will incorporate various aircraft sizes and proper flight behavior.

A Monte-Carlo type of simulative approach was selected and implemented to recreate more vivid traffic. Tab. 2 shows these parameters, mostly waypoints, and their variation (equal distribution). To compensate for the stochastic influence in the simulations, trial runs were performed to determine the minimal simulation time for stable results (3 hours of continuous landings or missed approaches respectively). In a first step, safety assessment of flight tracks was performed with the same arbitrary navigation tolerance values as before (chapter B.3) to generate results that are comparable to the analytic results. In a second step, safety assessment was repeated with dynamic ANP values (chapter II.C).

TABLE II. SIMULATION PARAMETERS AND THEIR VARIATION

Parameter	Value	Variation
landing speed (v_{ref})	120 knots	none
take-off speed (v_2)	160 knots	none
aircraft separation	3 NM	+0..20 s
touch-down location (TDZ representative)	450 m from threshold	none
decision height (missed approach)	200 ft altitude	+0..100ft
acceleration and rotation phase (take-off)	1500 m from threshold	+0..2000 m
straight climb out phase (take-off)	1000 m	+0..1000 m

2) Maximal Collision Probability - Comparison to Analytic Result: The highest collision probability values that will be found in the simulation run should be equivalent and directly comparable to the analytically derived critical cases. For this reason, these values were extracted from a first simulation run with disabled parameter variation. The results are shown in fig. 6, overlaid with the analytical results (dotted plots). In principle, the graphs show that the simulative approach is valid (and surpasses the analytic results in detail).

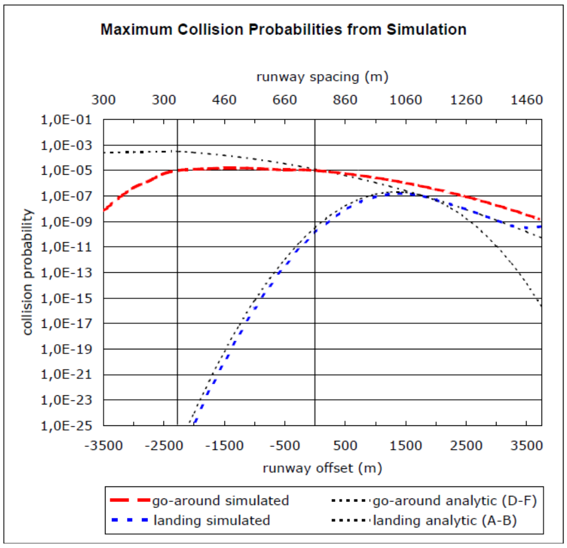

Figure 6. Maximum collision probabilities from simulation run

The plot for landings (dashed red plot) matches the analytically derived plot quite well. The changeover above 1600 m runway offset is due to the fact that the minimal distance is only determined by the critical case A-B until A and B align. After that, the minimal distance of the approach and departure paths becomes determinative and the dependency changes. The graph for missed approaches (dotted blue plot) equally diverts from the analytic results because not all path segments were considered when the critical cases were identified. Left of zero offset, the graph stays below our analytic values because the straight-out climb segment is not of infinite length (as assumed). Right of the zero offset, the values are higher, because the (formerly disregarded) fly-over segment takes effect. An undesired modeling effect raises the curve slightly further: when departing aircrafts turn, their probability functions extend into the missed approach path. The shape of location probability functions does not bend with the flown trajectory, as it ideally should. The effect pushes maximal values, but has small influence on average values, because it applies to rare constellations only.

3) Average Collision Probability – Discussion of Results: For continuous simulation data with parameter variations, average values of collision probability become meaningful. To create comparability to established TLS, the average was defined as temporal integral of systemwide collision risk divided by the number of landing or missed approach operations respectively. Trial runs determined the simulation time necessary to stabilize the results – the remaining variances shall reflect soley the influence of parameter variation.

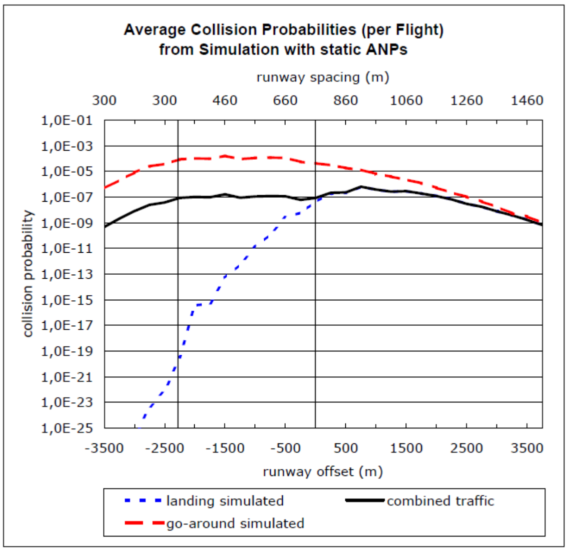

Figure 7. Average simulated collision probabilities for static ANP values

The results for standard arbitrary ("static") ANP values are shown in fig. 7. As expected, the parameter variation, which mostly spreads formerly fixed locations in the direction of runway offsets, leads to broader curves for both landings and missed approaches. In relation to the maximal values, the averages are lower, adding to said effect. The bend at the linear dependency's end (at -2300 m offset) is still, even more, visible. While both curves maintain their shape with parameter variation, landing operations (dotted blue plot) are affected more. The reason is simple: the critical distance (A-B) is directly affected by the parameter variation in the take-off location. For missed approaches, the flight tracks between conflicting aircraft are roughly parallel, which lessens this influence. Finally, we construct a combined graph for a one to one thousand operational traffic (landings and missed approaches). The graph (solid black plot) reveals a LoS that is somewhat constant in the familiar magnitude of $1 \cdot 10^{-7}$. The simulative approach and the assumptions are complex and certainly not generic. And although this graph does not explain the scientific foundation behind the 1/5 rule's design, the authors conclude that practical observations of a similar kind might have lead to the linear dependency of runway staggering.

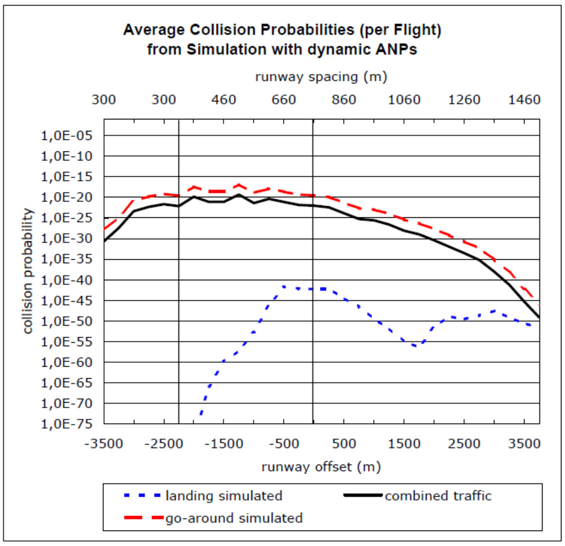

Figure 8. Average simulated collision probabilities for dynamic ANP values

Fig. 8 shows the same results for "dynamic" ANP values [17]. Since these are much smaller, reflecting good navigation performance in the TMA (e.g. consider ILS approach), the results differ greatly in magnitude (note the adapted scale). As a secondary result, the dependency on runway staggering increases greatly. The collision risk for landing operations becomes negligible by TLS standards. The shape of the curve indicates that safety hotspots exist, when runways are not staggered at all (-500-500 m offset) and when the staggering enables airborne arriving and departing aircrafts to interact (>1950 m offset). The operational traffic mix does not reveal any further information (other than a collision risk that barely exceeds $1 \cdot 10^{-20}$ per operation).

To conclude: Safety assessment on the simulative results produces a high fidelity towards the modeled scenario. Similar results are not easily produced through geometric analysis or safety assessment on critical distances. In particular, the 1/5-rule's design could not be comprehended through geometric analysis. The insight gained, though, greatly helps in understanding the simulative results. Safety assessment results with close-to reality parameter variation and static ANP values indicate that the 1/5 runway staggering rule does indeed lead to collision risk levels that resemble known TLS with respect to an operational traffic mix between landings and missed approaches. Applying the novelty of our safety assessment approach, adaptive parameterization with realistic ANP values, reveals that the technological collision risk considering state-of-the-art navigation technology lies far lower. The authors conclude that the 1/5 rule relates to earlier navigation aids (the oldest in service need to be considered), that the 1/5 rule might incorporate more complex considerations like weather influence, and that the scientific foundation for its design could likely be flight technical and navigational error modeled in a "static" probabilistic fashion.

IV. OUTLOOK

With this paper, we presented a quantitative safety assessment concept which proves to be applicable to practical problems, i.e. validating existing standards such as those put down in ICAO Annex 14 and PANS-OPS and to provide insight into the contributors of the air traffic system's overall safety. At this point, we have operationalized a technologically objective safety metric that conforms to the so-far promoted target levels of safety specified by ICAO and Eurocontrol. While this paper presented the application to a planning rule for the design of airports as a proof-of-concept, future work shall focus the dynamics of air traffic control, identifying controller strategies for risk mitigation, modeling procedures and human factors, and extensively simulating traffic. The safety metric shall take the role of a target function to evaluate simulated performance.

REFERENCES

[1] ICAO DOC 9859 AN/460, "Safety Management Manual (SMM)," International Civil Aviation Organization, Montreal, Canada, 2006.

[2] ICAO, "Annex 10 - Aeronautical Telecommunications, Volume 1," 6th Edition, International Civil Aviation Organization, Montreal, Canada, 2006.

[3] ICAO DOC 9830, "Advanced Surface Movement Guidance and Control Systems (ASMGCS) Manual," International Civil Aviation Organization, Montreal, Canada 2004.

[4] ICAO DOC 8168, "Procedures for Air Navigation Services – Aircraft Operations (PANS-OPS)," 5th Edition, International Civil Aviation Organization, Montreal, Canada, 2006.

[5] CAATS, "Safety Assessment Techniques Database," Nationaal Lucht- en Ruimtevaartlaboratorium (NLR), Amsterdam, Netherlands, 2005 (from http://www.caats.isdefe.es/home.html?dissemination, retrieved: 2010-02-10).

[6] I. Laudeman, S. Shelden, R. Branstrom, and C. Brasil, "Dynamic Density: An Air Traffic Management Metric," Report NAS/TM-1998-112226. NASA Ames Research Center, Moffett Field, California, USA, 1998.

[7] A.L. Breitler, M. Lesko, and M. Kirk, "Effects of sector complexity and controller experience onprobability of operational errors in air route traffic," Federal Aviation Association, Report DTFA01-95-C-00002, 1996.

[8] P. Kopardekar, "Dynamic Density – A Review of Proposed Variables, FAA NAS Advanced Concepts," Federal Aviation Association, Report ACT-540, 2000.

[9] J. Djokic, H. Fricke, M. Schultz, and C. Thiel, "Air traffic Complexity as a Safety Performance Indicator," Modern Safety Technologies in Transportation (MOSATT) Conference 2009, Zlata Idka, Slovakia, 2009.

[10] R.A. Paielli, and H. Erzberger, Paielli, "Conflict Probability Estimation for Free Flight," Journal of Guidance, Control, and Dynamics, Vol. 20, No. 3, May-June 1997.

[11] H. Fricke, "Integrated Collision Risk Modelling – CoRiM: An airborne Safety and Protection System for upcoming ATM Concepts," Berlin 2001.

[12] H. Blom, B. Bakker, M. Everdij, and M. van der Park, "Collision Risk Modeling of Air Traffic, "Nationaal Lucht- en Ruimtevaartlaboratorium (NLR), Amsterdam, 2004.

[13] M. Kietzmann and H. Fricke, „Entwicklung eines quantitativen Bewertungsmodells zur objektiven Beurteilung des Einflusses neuer Betriebsverfahren auf die Sicherheit im Luftverkehr," DGLR Jahrestagung 2004, Dresden, Germany.

[14] S. Kinnersley and I. Wilson, "INTEGRA Metrics & Methodologies Safety Metrics Technical Definitions", EUROCONTROL, Budapest, Hungary, 2000.

[15] ICAO DOC 4444 ATM/501, "Procedures for Air Navigation Services – Air Traffic Management (PANS-ATM)," International Civil Aviation Organization, Montreal, Canada, 2001.

[16] ICAO DOC 9613 AN/937, "Performance-based Navigation Manual (PBN)", 3rd Edition, International Civil Aviation Organization, Montreal, Canada, 2008.

[17] C. Thiel, „Untersuchung der Navigationsgenauigkeiten von Luftfahrzeugen im Flughafennahbereich – Modellierung und Implementierung dreidimensionaler Verteilungsfunktionen unter Berücksichtigung der Navgationsinfrastruktur an großen Verkehrsflughäfen," TU Berlin, Germany, 2009.

[18] C. Thiel and H. Fricke, "Collision Risk on final Approach – a radar-data based Evaluation Method to assess Safety," unpublished (to appear at ICRAT 2010).

[19] ICAO DOC 9643 AN/941, "Manual on Simultaneous Operations on parallel or near-parallel Instrument Runways (SOIR)," International Civil Aviation Organization, Montreal, Canada, 2004.

[20] ICAO, "Annex 14 – Aerodromes, Volume I, Aerodromes Design and Operations," 5th Edition, International Civil Aviation Organization, Montreal, Canada, July 2009.

[21] A320 Flight Manual.