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FAA ASSURE A21 Final Report Supplement E:
Evaluating Tradeoffs Between Costs and Benefits For Proposed sUAS Operation

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The FAA-Approved revision of FAA ASSURE A21 Task 3-2 includes four subtasks, of which Subtask 2 is:

> Defining a methodology/framework based on classical decision analysis for evaluating the tradeoffs between the costs and benefits associated with a proposed sUAS operation.

This brief note provides preliminary considerations on how the probabilistic risk assessment (PRA) framework developed in A21 Task 3, which has thus far focused on costs of sUAS operations, may be extended to also consider sUAS benefits. This note is organized as follows:

- §1: "Highly selective review of classical decision analysis"
- §2: "Specification of classical decision analysis to cost-benefit analysis of sUAS"
- §3: "Commercial sUAS BVLOS package delivery state of the art"
- §4: "Conclusion and next steps"

1 Highly selective review of classical decision analysis

Classical decision analysis is a complex and multifaceted discipline, many aspects of which have been well-established for decades. This review is therefore, of necessity, highly selective, and provides only the simplest possible sketch of one specific branch of the theory.

Let $A = (a_1, a_2, \ldots)$ be a denumerable set of distinct actions of which an actor must select one. Let $\Omega = (\omega_1, \omega_2, \ldots)$ be a denumerable set of outcomes, each of which is considered a "state of the world," in the sense that it specifies all environmental conditions that affect the outcome of the action. Let $p = (p_a, a \in A)$ denote a denumerable collection of probability distributions, indexed by each action a in A, where p_a is the probability distribution over Ω when action $a \in A$ is selected by the actor. Thus, each p_a is a denumerable collection of nonnegative numbers, say $p_a = (p_a(\omega), \omega \in \Omega)$, that sum to one, i.e., $\sum_{\omega \in \Omega} p_a(\omega) = 1$. Let there be k real-valued factors by which the outcome of the decision process is to be assessed, say $x = (x_1, \ldots, x_k)$, identified here as a *factor vector*, where the value taken by each of these k factors is determined by the outcome $\omega \in \Omega$, and as such these factors are real-valued random variables, denoted $\mathsf{x} = (\mathsf{x}_1, \ldots, \mathsf{x}_k)$, with the realization for outcome ω denoted as $x(\omega) = (x_1(\omega), \ldots, x_k(\omega))$, and the corresponding support of x denoted $\mathcal{X} = (x(\omega), \omega \in \Omega)$. The distribution on x is induced by the selection of the action a, i.e.,

$$\mathbb{P}(\mathsf{x} = x | a) = p_a(\omega), \ x = x(\omega), \ x \in \mathcal{X}, \ \omega \in \Omega. \tag{1}$$

Preferences among factor vectors $x \in \mathcal{X}$ induce preferences among outcomes $\omega \in \Omega$. This preference among factor vectors is translated into a real-valued utility function $u : \mathbb{R}^k \to \mathbb{R}$ that respects the preference ordering, i.e., $x \preccurlyeq x'$ iff $u(x') \geq u(x)$, where $x \preccurlyeq x'$ denotes factor vector x' is preferred to or considered equivalent to factor vector x. The expected utility associated with each action a is then

$$\mathbb{E}[u(\mathsf{x})|a] = \sum_{\omega \in \Omega} u(x(\omega)) p_a(\omega), \ a \in A. \tag{2}$$

Finally, the subset of optimal decisions, denoted $A^* \subset A$, contains those actions a that achieve the maximum expected utility over A, i.e.,

$$A^* = \operatorname*{argmax}_{a \in A} \mathbb{E}[u(\mathsf{x})|a]. \tag{3}$$

In reviewing the above model, it is evident that it requires specification of the following components:

1. Enumeration of the possible actions, A
2. Enumeration of the possible outcomes, Ω
3. Determination of the probability distributions p (over Ω, one for each element of A)
4. Identification of the k factors comprising the factor vector x, along with their value for each outcome in Ω, yielding the support $\mathcal{X}$
5. A preference relation over $\mathcal{X}$, or, equivalently, identification of a utility function $u : \mathbb{R}_k \to \mathbb{R}$ that respects the preference relation

With these items in hand, calculation of the optimal decisions A^* in (3) is straightforward.

2 Specification of classical decision analysis to cost-benefit analysis of sUAS

The discussion here outlines, in broad strokes, how the classical decision analysis framework described in §1 may be applied to a cost-benefit analysis of a proposed sUAS CONOPS. Below, brief comment is given regarding how the model components listed in §1 might be specified in this context. In all cases, preference is given to parsimony over fidelity, guided by the objective of describing the simplest possible model in this context.

1. *Enumeration of the possible actions, A.* Viewing the decision time to be the instant before the CONOPS is to be initiated, the simplest possible actions are $A = \{a_1, a_2\}$, where a_1 corresponds to the decision to abort the CONOPS and a_2 correponds to the decision to proceed with the CONOPS. In other contexts, the possible actions may include various routes to be taken by the sUAS.
2. *Enumeration of the possible outcomes, Ω.* The enumeration of possible outcomes may extend from the concepts of hazard cause (hc) and hazard outcome (ho) enumeration, as described in the A21 Task 3 reports. Namely, one may approach enumeration of Ω via the taxonomy $\Omega = \Omega^{\mathrm{hc}} \times \Omega^{\mathrm{ho}} \times \Omega^{\mathrm{bo}}$, where:

    - Ω^{hc}: set of possible hazard causes
    - Ω^{ho}: set of possible hazard outcomes
    - Ω^{bo}: set of possible benefit outcomes

    Here, Ω^{bo}, the set of benefit outcomes, is an enumeration of the possible state of the environment surrounding the sUAS that informs or impacts the extent to which the CONOPS achieved, indirectly or directly, a positive impact on the state of the world. This may include, for example, (un)successful package delivery, (un)successful acquisition of data, or even (un)successful mitigation of a perceived threat; the specific choice of Ω^{bo} would be determined by the CONOPS. Under this taxonomy, an overall outcome $\omega \in \Omega$ consists of three components, one from each set above, i.e., $\omega = (\omega^{\mathrm{hc}}, \omega^{\mathrm{ho}}, \omega^{bo})$, with $\omega^{\mathrm{hc}} \in \Omega^{\mathrm{hc}}$, $\omega^{\mathrm{ho}} \in \Omega^{\mathrm{ho}}$, and $\omega^{\mathrm{bo}} \in \Omega^{\mathrm{bo}}$. Recall from the discussion of $\Omega^{\mathrm{hc}}, \Omega^{\mathrm{ho}}$ that it is convenient to introduce a "null" outcome for each, denoted by ϕ, e.g., $\omega^{\mathrm{hc}}_{\phi}$ is the null hazard cause (i.e., nothing has gone wrong) and $\omega^{\mathrm{ho}}_{\phi}$ is the null hazard outcome (i.e., there has been no negative impact on the environment). In a similar vein, it is natural to include $\omega^{\mathrm{bo}}_{\phi} \in \Omega^{\mathrm{bo}}$ as the null benefit outcome, which likely means that the mission objectives of the CONOPS have been achieved. Recall also from the discussion of $\Omega^{\mathrm{hc}}, \Omega^{\mathrm{ho}}$ that not all pairs $(\omega^{\mathrm{hc}}, \omega^{\mathrm{ho}})$ are considered possible, e.g., $(\omega^{\mathrm{hc}}_{\phi}, \omega^{\mathrm{ho}})$, for $\omega^{\mathrm{ho}} \in \Omega^{\mathrm{ho}} \setminus \{\omega^{\mathrm{ho}}_{\phi}\}$ is assumed impossible, i.e., there can be no non-null hazard outcome under the null hazard cause. The main point is that, under the model for an actual CONOPS, the cardinality of Ω under this taxonomy may well be sparse, i.e., it may hold that $|\Omega| \ll |\Omega^{\mathrm{hc}}||\Omega^{\mathrm{ho}}||\Omega^{\mathrm{bo}}|$.
3. *Determination of the probability distributions p (over Ω, one for each element of A).* The probability distributions $p_a = (p_a(\omega), \omega \in \Omega)$ over outcomes Ω for each action $a \in A$ will need to be obtained from a combination of *i*) empirical measurement / testing, *ii*) mathematical modeling, and *iii*) simulation. It is beyond the scope of this note to address this issue here, other than to emphasize that if the outcome space

Ω is defined using a taxonomy like the one described above, then these distributions will likely be estimated component-wise, as is done with hazard causes and hazard outcomes in the proposed PRA framework, i.e.,

$$p(\omega) = p(\omega^{\mathrm{hc}}, \omega^{\mathrm{ho}}, \omega^{bo}) = p(\omega^{\mathrm{hc}})p(\omega^{\mathrm{ho}}|\omega^{\mathrm{hc}})p(\omega^{bo}|(\omega^{\mathrm{ho}}, \omega^{\mathrm{hc}}). \tag{4}$$

Here, *i)* $p(\omega^{\mathrm{hc}})$ is the (unconditional) probability of hazard cause ω^{hc} occurring, *ii)* $p(\omega^{\mathrm{ho}}|\omega^{\mathrm{hc}})$ is the conditional probability of hazard outcome ω^{ho} occurring conditioned on hazard cause ω^{hc} having occurred, and *iii)* $p(\omega^{bo}|(\omega^{\mathrm{ho}}, \omega^{\mathrm{hc}})$ is the conditional probability of benefit outcome ω^{bo} occurring conditioned on both hazard cause ω^{hc} and hazard outcome ω^{ho} having occurred. The existing "cost"-focused PRA uses both *i)* and *ii)*, the proposed "benefit" extension would require specification or estimation of *iii)*.

4. *Identification of the k factors comprising the factor vector x, along with their value for each outcome in Ω, yielding the support $\mathcal{X}$.* The k factors here each represent a quantifiable, or at least orderable, measure of the costs or benefits associated with the CONOPS, and should include both benefits and cost components. Sample factors may include quantification of the costs associated the sUAS hitting the built environment or hitting one or more people, or quantification of the benefits associated with the sUAS delivering its package, or gathering information, or mitigating a threat. Note, there is no need for the costs or benefits in the different factors to be accounted in the same units. All that is required is that, given any two factor vectors, say $x = x(\omega)$ and $x' = x'(\omega')$, the analyst can specify a preference on (x, x'). Also, in quantifying the values of a given factor under different outcomes, care should be taken to incorporate both direct and indirect effects. For example, the cost associated with an outcome in which the package delivery CONOPS is not attempted include costs incurred in ensuring the package is delivered via another means, e.g., ground courier.
5. *A preference relation over $\mathcal{X}$, or, equivalently, identification of a utility function $u : \mathbb{R}_k \to \mathbb{R}$ that respects the preference relation.* The specification of the preference relation over the support $\mathcal{X}$ is perhaps the most difficult task, on account of it requires specifying preferences over outcomes that are widely disparate in their effects, e.g., a preference over factor vectors that may include (un)successful completion of the CONOPS along with possible crashes into the built environment and/or people. Naturally, such assessments should be done with great care, and by qualified professional economists trained in government policies and procedures for cost-benefit analysis.

3 Commercial sUAS BVLOS package delivery state of the art

In order to convey the scope and range of benefits from sUAS BVLOS operations, it is helpful to consider the state of the art of the commercial sUAS BVLOS package delivery market. The articles below describe sUAS package delivery services by Alphabet (parent company of Google), Amazon, and UPS.

- "Alphabet's drone delivery service Wing hits 100,000 deliveries milestone", *The Verge*, James Vincent, August 25, 2021.[1] This article describes 100,000 deliveries in Australia, the United States, and Finland by Alphabet's drone delivery service Wing. Deliveries range from vaccines and blood samples to groceries.
- "Wing approaches 100,000 drone deliveries two years after Logan, Australia launch", *TechCrunch*, Brian Heater, August 25, 2021.[2]. This article covers the same topic as the previous one. Drones are limited to a range of six miles, fly at an altitude of 100-150 feet, and hover at around 23 feet at destination, lowering the package by tether.
- "A first look at Amazon's new delivery drone", *TechCrunch*, Frederic Lardinois, June 5, 2019.[3] This article discusses Amazon's six-rotor drones designed for package delivery which, like Alphabet's Wing, will use

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[1] `https://www.theverge.com/2021/8/25/22640833/drone-delivery-google-alphabet-wing-milestone`

[2] `https://techcrunch.com/2021/08/25/wing-approaches-100000-drone-deliveries-two-years-after-logan-australia-launch/`

[3] `https://techcrunch.com/2019/06/05/a-first-look-at-amazons-new-delivery-drone/`

vertical take-off and landing. Amazon has included a suite of environmental sensors and associated machine learning algorithms to ensure operational decisions are within required safety standards.

- “Amazon wins FAA approval for Prime Air drone delivery fleet”, *CNBC*, Annie Palmer, August 31, 2020.[4]. This article also covers Amazon’s package delivery service, Prime Air, focusing more on the regulatory approval aspects.
- “UPS wins first broad FAA approval for drone delivery”, *CNBC*, Leslie Josephs, October 1, 2019.[5]. This article describes the approval by the FAA for UPS’s proposed drone delivery service. UPS has already begun testing medicine and drug delivery on hospital campuses.

4 Conclusion and next steps

The conclusion from the presentation in §2 is that the analytical structure provided by the field of classical decision analysis is an appropriate framework for considering the tradeoff between costs and benefits in evaluating proposed sUAS operations. What is significant about this discussion is the indication that the methods described in detail in the Task 3-3 report for calculating posterior distributions on hazard outcomes can be applied within this decision analytic framework to estimate some of the required probability distributions based on objective data. They similarly can be used to support sensitivity analyses. The next steps in applying classical decision analysis to cost benefit analysis of proposed sUAS operations would be to develop the five quantities listed in §2. In addition, this framework would facilitate sensitivity analyses.

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[4] `https://www.cnbc.com/2020/08/31/amazon-prime-now-drone-delivery-fleet-gets-faa-approval.html`

[5] `https://www.cnbc.com/2019/10/01/ups-wins-faa-approval-for-drone-delivery-airline.html`