

Planning the Unplanned Experiment: Towards Assessing the Efficacy of Standards for Safety-Critical Software

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While software in industries such as aviation has a good safety record, little is known about whether standards for software in other safety-critical applications “work” — or even what that means. Safe use of software in safety-critical applications requires well-founded means of determining whether the software is fit for such use. It is often implicitly argued that software is fit for safety-critical use because it conforms to an appropriate standard. Without knowing whether a standard “works,” such reliance is an experiment and without carefully collecting assessment data, that experiment is unplanned. To help “plan” the experiment, we organized a workshop to develop practical ideas for assessing software safety standards. In this paper, we relate and elaborate on our workshop discussion, which revealed subtle, but important, study design considerations and practical barriers to collecting appropriate historical data and recruiting appropriate experimental subjects. We discuss assessing standards as written and as applied, several candidate definitions for what it means for a standard to “work,” and key assessment strategies and study techniques. Finally, we conclude with a discussion of the kinds of research that will be required and how academia, industry and regulators might collaborate to overcome these noted barriers.

Introduction

Safe use of software in safety-critical applications requires well-founded means of determining whether the software is fit for such use. While software in industries such as aviation has an excellent safety record, the fact that software has contributed to deaths and injuries suggests that it is vital to justify high confidence in safety-critical software. Despite the danger of relying on software with properties that cannot be guaranteed, developers are building ever-more-complex software for safety-critical applications — sometimes for good reasons. For example, enhanced ground proximity warning systems (EGPWS) — far too complex to be implemented in simple hardware — save lives by preventing controlled flight into terrain (CFIT) accidents [Ref. 1]. Today, it is often implicitly argued that software is fit for use in a safety-critical application because it conforms to

a standard such as RTCA DO-178C [Ref. 2], ISO 26262 [Ref. 3] or IEC 61508 [Ref. 4]. But little is known about whether such standards “work,” or even what it means for them to work. Deciding to accept the risk associated with using software based on its conformance to a standard, without knowing whether that standard works, is to perform an experiment in which developers build software and only later find out if the systems incorporating it are safe. Moreover, unless developers, operators and regulators carefully collect well-chosen data and use this to assess the standard, this experiment is *unplanned* and thus unlikely to support definitive conclusions about whether the standard works.

We organized the *Planning the Unplanned Experiment: Assessing the Efficacy of Standards for Safety-Critical Software* (AESSCS 2014) workshop to bring together academia, industry and regulators to develop practical ideas for assessing standards for software in safety-critical applications [Ref. 5]. In this paper, we relate and elaborate on the workshop discussion (including ideas that we do not necessarily endorse). Assessing standards will require the cooperation of academia, industry and regulators. Toward achieving this, we contribute discussion and analysis of what to assess (e.g., the standard as written, the standard as applied or a commonly used combination of safety evidence), what it might mean for a standard to “work,” strategies for assessing standards, study methods and suggestions for moving forward. We conclude with thoughts about the kinds of research that will be required to assess standards, along with how academia, industry and regulators might collaborate to overcome obstacles such as those related to data confidentiality and the representativeness of experimental subjects.

Salient Characteristics of Standards for Software in Safety-Critical Applications

Standards for software in safety-critical applications vary, but they also exhibit commonalities. Typical standards comprise a number of *assurance requirements*, most of which specify activities that developers must perform or qualities that development artifacts must have. For example, *Software Considerations in Airborne Systems and Equipment Certification* (DO-178C) re-



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quires “reviews and analyses of high-level [software] requirements” to “ensure that the ... functional, performance, and safety-related requirements of the system are satisfied by the high-level requirements” [Ref. 2]. Such assurance requirements are called *objectives* in DO-178C, but are known by other names in other standards. Most standards for software in safety-critical applications are sometimes called *prescriptive* or *process-based* because of their many assurance requirements and because these are expressed in terms of a model software process and life cycle. However, developers are typically permitted to meet the spirit of each assurance requirement in any appropriate manner. For example, DO-178C explicitly permits the use of alternative methods of meeting its assurance requirements as agreed with certifiers [Ref. 2].

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Most standards’ assurance requirements are only indirectly related to the property of interest (e.g., system safety). For example, no assurance requirement

of DO-178C specifies a direct measure of software contributions to system safety (or even of software correctness); instead, each relates to assessable actions or properties, such as having reviewed the software requirements or achieved specified structural test coverage. Thus, standards could be seen as implicitly embodying a *recipe* for indirect software safety assessment. Many distinct recipes might conform to a given standard, but there are a limited number of canonical recipes. The recipe that seems most common includes software requirements defined at multiple levels of software abstraction, reviews and analyses of these to show traceability and refinement and software testing at the unit, integration, software and system levels.

Standards are deliberately flexible with regard to the development and assessment approach, so as not to stifle progress. Some standards require the construction of a *safety case* which is typically defined as “a structured argument, supported by a body of evidence that provides a compelling, comprehensible and valid case that a system is safe for a given application in a given environment” [Ref. 8]. While some standards require specific evidence to appear in a safety case [e.g., Ref. 3], others offer fewer constraints [e.g., Ref. 9]. Regardless of whether conformance evidence includes a safety case, a report on a safety case or a DO-178C-style Software Accomplishment Summary [Ref. 2], flexibility raises the possibility that the efficacy of a standard will depend on the recipe used. Thus, the efficacy of each recipe might be at least as interesting as the efficacy of each standard.

Attempts to Assess Standards for Software in Safety-Critical Applications

The issue of whether standards for software in safety-

critical systems “work” — and how to improve them — has been a topic of discussion for many years [Refs. 10–13]. There have been studies of the efficacy of such standards [Ref. 14] and blue-ribbon inquiries into the difficulty of creating and certifying dependable software [Ref. 15]. There are research papers that raise questions about the role of standards in achieving safety and sketch studies to answer those questions [Ref. 16]. There are papers about the efficacy of techniques that standards require or recommend — e.g., conformance to coding standards such as MISRA C [Ref. 17] — though definitive evidence of efficacy is rarely available for any such technique [Ref. 15]. There are even standards for standards [Ref. 18]. As far as we know, however, AESSCS 2014 was the first workshop dedicated to the question of how to rigorously assess whether such standards “work.” Many ideas brought to the workshop have been stated elsewhere, sometimes by people other than the workshop participants. The value of the workshop is in using those ideas to assemble a coherent set of research questions and to sketch studies that might address those questions [Refs. 7, 19–25].

Much of what has been said against standards comes down to complaints about the costs of conformance assessment and of mandated development and verification activities [e.g., Ref. 15], complaints that standards focus too much on process and too little on broader issues of what the software does [e.g., Ref. 15], and complaints that the efficacy of required and recommended techniques is largely unknown [e.g., Ref. 15]. Some have criticized a similar standard, the Common Criteria for Information Technology Security Evaluation, for having seemingly little impact on security metrics such as the number of known vulnerabilities [Ref. 15].

Much of what has been said in support of standards comes down to examples of problems that must be addressed or observations that industries using a given standard have a good safety record. For example, one might observe that inadequate configuration management would undermine software verification and validation results, and conclude that a good standard should require configuration management. But a standard might address each known necessary condition and yet not “work,” either because its assurance requirements are insufficiently effective or because a key condition remains unknown and unaddressed. One researcher claims that current standards-based approaches have “proven in some industries (such as aviation) to have lowered accident rates dramatically” [Ref. 26]. But the argument from history is unconvincing. First, correlation is not causation [Ref. 27]: Confor-

mance and safe operation might occur together, even if the latter is caused by a third factor, such as developers’ care and attention [Ref. 16]. Second, the correlation has not been measured and would be hard to measure accurately: Many applications do not offer large-enough exposure to assess the frequency of very rare events, and multiple versions of a standard might have been used over the years. In addition, anecdotes about lenient assessors suggest differences in how standards are interpreted and applied. It is also possible that a standard might work better for a system of the past than for a new system featuring a more complex processor, a more integrated and networked platform, more complex software functions or more autonomy. The community needs better evidence that standards are fit to support safety-related decisions.

What it Means for a Standard for Software in Safety-Critical Applications to “Work”

Assessing whether a standard “works” requires identifying exactly what the term “work” means in this instance. Ideally, each standard would define this for itself. But while some standards include statements about the standard’s aims or contributions, these are rarely testable hypotheses about the standards’ effects on safety or correctness. Some are vague, others are belied by the body of the standard and still others sidestep important issues. For example, ISO 26262 promises “guidance to help avoid [risks due to the failure of electrical or electronic components in automobiles] by providing appropriate requirements and processes” [Ref. 3]. But what does it mean to “help avoid” risk? The statement does not promise a result that will satisfy any of the well-known theories of residual risk acceptability [Ref. 28]. It is perhaps unfair to expect that it would: ISO 26262 is an industry consensus document meant to apply across a diverse supply chain. Nevertheless, to determine whether a standard “works,” researchers need a testable definition of “work.” Participants in AESSCS 2014 identified (a) a crucial distinction between the goals of correctness and system safety, (b) several definitions of what it means for a standard to achieve one of those goals and (c) cross-cutting concerns, such as cost effectiveness and applicability. The definitions can be organized into four categories:

- Bounding uncertainty in a claim about software behavior or contributions to system safety
- Addressing the risk from the most likely and/or consequential mistakes
- Promoting developer competence

- Giving certifiers a tool to improve safety

It remains to be seen which definition(s) will yield practical assessments that offer sufficient grounds for making rational decisions about whether a given system is acceptably safe or for setting certification policy.

Safety Versus Correctness

Some standards for software in safety-critical applications are focused on correctness rather than safety: Their assurance requirements are mainly about whether the software behaves as specified, not how that behavior affects system safety. For example, DO-178C [Ref. 2] assumes software requirements derived from a system-level safety analysis, such as one that might be performed in accordance with SAE ARP4754A [Ref. 29]. The standard's assurance requirements aim to show that the delivered software meets its requirements, but safety-related requirements are not singled out for special care. DO-178C specifies software development assurance levels in terms of the consequences of software failure, but excludes all safety analyses from its scope. Other standards define and require safety analyses. For example, like DO-178C, Part 6 of ISO 26262 contains many assurance requirements related to verifying software correctness [Ref. 3]. But unlike DO-178C, ISO 26262 gives guidance for safety assessment of systems containing software — part 3 defines a hazard and risk assessment process. This guidance is limited in scope to the safety impact of the failure of individual electrical and electronic “items.” The standard's assurance requirements would apply to the design and implementation of an electronic stability control system *if* the manufacturer fits one. But the decision of whether to fit such a system at all might have a greater impact on safety.

Correctness is not a sufficient condition for safety. Safety might depend more on decisions about *what* to build: There is some evidence to suggest that requirements defects are a bigger problem than implementation defects [Refs. 30 and 31]. Automation, human factors and security are all key considerations. The choices of what to automate and how to automate it are important concerns in aviation [Ref. 32], and trends towards assisted and autonomous driving suggest that automation is also a growing concern in the automotive domain [Ref. 33]. Airborne software might

meet its requirements yet create challenges for aircraft maintainers, leading to a higher risk of maintenance error — and thus of an accident — than an alternative design. Designers might cut costs by implementing avionics functions in a thematically unrelated unit with surplus processing power, causing flight crews to struggle to understand how the error messages they receive relate to the symptoms they experience. Building automobile radios with speed-sensitive volume controls increases passenger comfort, but requires a data link between the radio and the relevant engine control unit(s) that might be a vector for deliberate attack on a vehicle's lights or brakes [Ref. 34]. While safety standards traditionally exclude security concerns, the potential for deliberate attack to compromise safety

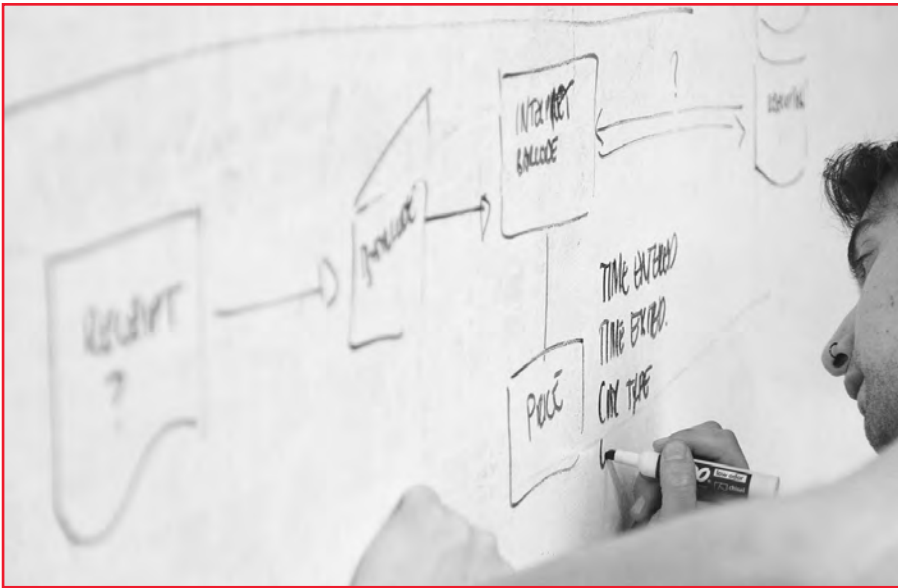
cannot be ignored; a complete approach to safety must weigh the impact of design choices that affect both. But, partly to avoid programmers having to be safety experts, most standards for software in safety-critical applications focus more on correctness than on safety. Accordingly,

some definitions of “work” must consider both safety and correctness forms. Moreover, it might be useful to study the safety impact of combinations of standards.

Bounding Uncertainty in Safety or Correctness Claims

A standard for software in safety-critical applications might be said to “work” if its use reduces and bounds the uncertainty in a behavior or safety claim of interest. For example, DO-178C claims to “provid[e] the aviation community with guidance for determining, in a consistent manner and with an acceptable level of confidence, that the software aspects of airborne systems comply with airworthiness requirements” [Ref. 2]. This definition implicitly acknowledges that it is impossible for conformance to a standard to *entail* a behavior or safety claim (unless that claim is trivially true, in which case the standard is irrelevant). Instead, the standard is meant to increase the likelihood of spotting mistakes that would compromise system safety before systems are deployed. This definition of “works” is related to the “Filter Model” of safety-critical system certification, in which certification comprises a *filter* and a *decision procedure* [Ref. 35]. Each assurance requirement is a filter used to identify faults in a system. As in the “Swiss

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Cheese” accident model [Ref. 36], each filter might catch defects that other filters in the same standard miss. Collectively, the filters allow certifiers to judge “whether faults remain that would subject the public to an unacceptable level of operational risk” [Ref. 35].

The bounding uncertainty definition of what it means for a software safety standard to “work” has the virtue of being the most relevant to decisions about whether to deploy, continue operating or improve software in safety-critical applications. The present state of knowledge is too limited to claim that a standard either works or does not work using this definition. Some standards might not. But this definition captures what many speakers mean when they say that a standard “works.” Thus, it might help to define the meaning of an assessment against a different definition.

Addressing the Risk of Specific Mistakes

A standard for software in safety-critical applications might be said to “work” if its use makes developers less likely to make (or more likely to catch) a set of mistakes of interest. This set might be drawn from research or lessons learned from accidents and incidents. Ideally, the set would include the mistakes that give rise to the greatest risk because they occur frequently or lead to the most severe accidents.

This definition differs from the previous one in that its focus is limited to specific contributions to uncertainty. To the degree that a system is like prior systems, addressing the ways in which those systems went wrong should make the system safer. This definition has the virtue of focusing attention on factors that are known to matter. However, addressing only such factors might not lead to safety where the application or development techniques are novel. For example, prohibiting

most backward branches might reduce the incidence of control-flow problems in assembly language programs, but such a rule is not applicable to software written in most high-level languages.

Promoting Developer Competence

A standard for software in safety-critical applications might be said to “work” because it promotes developer competence, either by teaching good practice or acting as a buffer against entry incompetent developers or organizations. While we would not recommend that developers learn to build critical systems *solely* by reading standards, a standard might (in part) have a pedagogical effect. Developers read the standard, come to understand its assurance requirements and seek information about the recommended means of satisfying these. In so doing, they might gain knowledge and develop habits that would improve their systems, even if conformance were (unexpectedly) never assessed. A standard might instead preclude the development of safety-critical systems by people who lack the requisite skills and experience, and organizations that do not adopt best practices. That is, the standard — or perhaps its compliance enforcement regime — might pose a difficult-to-surmount barrier to people whose work might yield unacceptable risk, without unduly impeding those who would produce acceptably safe systems with or without the standard. Several AESSCS participants expressed the opinion that if you took the standards away from the best teams, they would likely carry on building acceptably safe software.

Giving Certifiers a Tool for Improving Safety

A standard for software in safety-critical applications might be said to “work” because it gives certifiers a tool

for improving safety or blocking the deployment of unsafe systems. In this view, a standard's assurance requirements do not need to be unambiguous, perfectly bound confidence in safety, filter out unsafe systems or teach best practice." Developers are motivated by the possibility that assessors will refuse to certify compliance with the standard, either because compliance is mandated by law or regulation, or because a mark of compliance is perceived to add value. This motivation might encourage developers to follow better practices than they otherwise would. Where it doesn't, assessors might agree to certify systems only if developers agree to use a safer design or better tools or practices. In this view, a standard's assurance requirements need not be unambiguous, nor need they perfectly bound confidence in safety, filter out unsafe systems or teach best practice. If assessors can determine whether a given system is acceptably safe or whether an alternative would be safer, the leverage afforded by the certification regime could allow them to enforce or improve safety.

Cost-effectiveness

The definitions of "work" given above relate to standards' effects on safety or correctness. But standards also impact the cost of development and certification. Decisions about whether to use a standard, which standard to use and what assurance requirements to include in a standard might be made based on whether the standard is cost effective. Decisions about whether a safety improvement is worth its cost are unavoidably political. Nevertheless, a well-planned scientific assessment of standards might produce data that could inform such determinations. For example, consider a study that compares the effect of two standards on confidence in software correctness. If the study design can answer the question: "*Which works better?*" but not "*By how much?*," the study would not provide the information needed to make a decision based on cost effectiveness.

Applicability

Questions of whether a standard "works" need to be asked and answered considering a scope of systems of interest. A standard that is applicable to some systems might be inapplicable to others — and this is not merely a matter of domain. For example, DO-178C's assurance levels are defined in terms of software's effect

on the aircraft and its occupants [Ref. 2]. But the destruction of a remotely piloted or autonomous aircraft might be far less important than its interference with an aircraft carrying crew or passengers. A standard providing assurance that the aircraft does not collide with people or vehicles carrying people might be more cost effective for such aircraft.

A Standard's Text, its Application or its Recipe(s): What Is the Target of Evaluation?

The power of a study to answer specific questions related to standards depends (in part) on the target of evaluation: Does the study assess the standard as written, the standard as applied or a recipe that can be used with the standard? Each choice of target has advantages and disadvantages; none is a perfect choice for all assessment purposes.

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The Standard As Written

One could assess the text of a standard as written. For example, one could review the text for ambiguity in its assurance requirements or to see whether there are assurance requirements aimed at eliminating or catching a given kind of error. One could even couple what is known about the efficacy of safety and development techniques with analysis of the text to analyze where claims made on the basis of conformance might be weak. For

example, one could identify a claim that conformance to a standard was used to support, extract the argument implicit in the standard's assurance requirements and internal commentary, and critically examine that argument for gaps and flaws, some of which correspond to ways in which the standard could be improved [Ref. 37].

There are at least three advantages of examining the standard as written. First, the text of the standard is available to everyone who can afford it. Unlike a study of a system's history, there are no intellectual property or privacy concerns that would limit access to the standard's text. Second, it is easier to study a single, fixed thing. Unlike a study of a standard as applied, the study procedure need not account for variance in how the standard is interpreted. Third, many study designs are simpler than studies of the standard as applied. For example, review of a standard's text does not require extensive data collection and can be done by a single researcher working alone.

There are at least two disadvantages of examining a standard as written. First, the text might be non-specific, vague or (mis-)interpreted to serve political purposes, leading the conformant practice to be both highly variable and different from what a reader of the text might envision. Second, the relationship between an assurance requirement's text and its effect on safety or correctness might not be known. If it is not possible to predict practice from the standard's text, analysis of the text might not predict whether the standard "works" when applied in all intended or permitted contexts. We note that it might not be possible to eliminate variability in practice: Many standards deliberately allow developers to use better techniques than those imagined by the writers, where appropriate, and some standards are intended for a broad range of applications. For example, one safety standard applies to defense systems as diverse as soldiers' personal equipment and aircraft carriers [Ref. 8.]

The Standard As Applied

One could assess a standard as applied. For example, one could review bug reports, incident reports and accident reports to determine whether conformance with a standard at a higher integrity level corresponds to lower prevalence of dangerous faults [Ref. 23]. One could also compare records for systems built to different standards to see if one standard is associated with a lower rate of a specific mistake than another.

The obvious benefits of assessing a standard as applied are that assessment results can account for variations in how the standard is interpreted and for any mechanism by which its text might affect safety or correctness. For example, if defect rates are studied across a representative sample of software development efforts that conform to DO-178C (which might be difficult in practice), the results should generalize to other applications for which that standard is appropriate. If developers' office layout (e.g., offices vs. cubes) has a significant effect on the number and kind of defects introduced during coding, that effect might be visible in study data as a variance in defect rates that cannot be explained in terms of the independent variables identified in the study design.

The obvious disadvantages of assessing a standard as applied are difficulty, the possibility of noisy data and the possibility that the studied population might differ from the population of interest. Standards are applied mainly by private commercial firms that might not consent to release relevant data — perhaps out of concern that doing so might allow competitors to duplicate their success or press a legal claim. Variability in

how standards are applied might lead to noise in measured values that makes it difficult to draw conclusions. There is also the possibility that, as software development and assessment methods evolve and applications change, the population documented in the records might differ from the population of interest in a way that makes study conclusions inapplicable.

The Standards' Recipes

One could instead assess the recipes used to conform to standards. For example, one could determine the distribution of dangerous defects discovered in software developed using review to show requirements correctness, source code developed in the SPARK (Ada) programming language using a correct-by-construction approach [Ref. 38], a Real-Time Operating System (RTOS) with fixed-time partitioning, and testing that achieves Modified Condition/Decision Coverage (MC/DC) [Ref. 39].

The primary advantage of assessing the recipe rather than a standard itself is that the results support conclusions that hold, to some degree, in any context in which the recipe can be used, including developments that conform to goal-based standards [Ref. 9]. The disadvantage is that, unlike assessment of the standard as applied, it will be unclear whether the results reflect any effect from the standard or the certification process, other than limits on the recipe employed. For example, suppose that the knowledge that third-party certifiers will audit their work prompts development organizations to use better practices than they would if conformance were assessed in-house. If that is true, researchers studying examples of the recipe in a third-party certification context might find better outcomes than developers following the same recipe in an in-house conformance assessment context could reasonably expect to achieve.

Strategies for Assessing Standards for Software in Safety-Critical Applications

After identifying a hypothesis and a target of evaluation, researchers must choose an assessment strategy. In this section, we discuss four strategies. Again, none is a magic bullet: Each has advantages and disadvantages.

Measuring the Effect

One might assess a standard using a metric such as accident or incident rate, or number of defects (total and safety-related) discovered. For example, one might compare the number of safety-relevant defects found in software post deployment across software developed in conformance with different standards.

The advantages of this direct approach are simplicity and the elimination of needing to understand which factors impact overall effect and by how much. But there are at least three disadvantages to this approach. First, accidents and incidents might occur too infrequently to yield statistically significant results. In transport aircraft, for example, developers aim to make certain accidents unlikely over the operating lifespan of all systems of that type. Second, correlation is not causation: Some unappreciated difference between the application domains in which two standards are used, rather than the difference between the standards themselves, might be the actual cause of observed differences. Third, system developers and operators might be reluctant to disclose relevant data for reasons previously discussed.

Assessment by Parts

One might assess a standard or recipe by separately assessing the effectiveness of each of its assurance requirements or ingredients and then inferring an assessment of efficacy of the whole. For example, one might capture and then assess a standard's implicit argument as described earlier [Ref. 37]. Evaluating a recipe by parts would assess the efficacy of each technique, such as the effect of formalizing requirements [Ref. 21].

The advantage of this approach is that the efficacy of individual techniques might be shown by experiment, which is capable of demonstrating causality and justifying great confidence. But there are at least three disadvantages. First, it might be difficult to identify (or obtain agreement on) the standard's argument. SC-205 — the committee charged with producing DO-178C [Ref. 2] — produced a rationale document with brief discussions of the reasons behind some specific objectives, but this rationale is not an overall argument [Ref. 40]. Second, few such experiments have already been done. For example, there are differing opinions about the efficacy of testing that achieves MC/DC and there are little empirical data in the public domain. Third, the value of the whole might not depend *solely* on the individual values of its parts [Ref. 39]. For example, the efficacy of a technique might depend in part on whether it is deployed in conjunction with other specific techniques. The needed studies might be *very* specific.

Testing Necessary Conditions

One might assess a standard by identifying necessary conditions or ways in which it might *not* “work” and assessing each. For example, one might suppose that unambiguous assurance requirements are a prerequisite for a standard to work and survey assessors to determine whether they interpret objectives identically.

Several AESSCS participants proposed testing necessary conditions. McDermid proposed finding out if standards work better at higher integrity levels [Ref. 23]. Fusani and Lami questioned whether conformance can be assessed practically [Ref. 20]. Holloway and Johnson proposed investigating whether safety assessors have the skills and education necessary to assess the safety arguments required by some standards [Ref. 22]. Ashmore, Rushby, Littlewood and Strigini explore conditions necessary for assessing quantified software reliability [Refs. 19 and 24]. Wiels proposed an *abstraction view* model of certification that defines necessary conditions that might be evaluated in this way [Ref. 25]. In the model, certification is analogous to verifying software by verifying a formal abstraction of it. If conformance is to imply correctness, the standard's abstract view must be sound, tractable and precise. That is, the abstraction must “defin[e] more behaviors than the actual behaviors of the program,” conformance assessment must be practical, and nonconformities should correspond to ways in which the software is incorrect.

The advantage of this strategy is the ease of assessing a specific condition rather than a standard's overall effect. For example, configuration consistency could be assessed through auditing. The disadvantage of this strategy is that it can reveal problems, but not show efficacy: The unsatisfied necessary condition might remain unknown.

Solving the Problems of the Past

One might assess a standard by determining how well it solves past problems. For example, suppose that several systems in an application domain overrun response time deadlines and that a new version of the relevant standard includes new assurance requirements meant to improve confidence that deadlines will be met. One might monitor software that conforms to the new version of the standard and, if fewer overruns are seen in practice, conclude that it works better than the old version.

This strategy has the advantage of focusing on factors known to be important — some things that remain unknown might not matter in practice. However, it has at least two disadvantages. First, it is difficult to determine whether a standard introduces new problems as side effects. Second, as with the other strategies, software might begin to fail in ways not seen in the past as new applications are tackled and new development techniques introduced.

Research Methods

Once researchers have identified a hypothesis, target of evaluation and assessment strategy, they must



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Historical Study

One might assess a standard using historical data. For example, researchers might use defect logs to measure the correctness of software developed in conformance to a standard. Researchers might count accidents and incidents as a measure of the system safety impact of software developed in conformance to a standard.

The advantage of historical study is that there is more data about software that has been used for years than about software that has never been fielded. Although some events might still be too rare to draw significant conclusions about, history offers far more exposure than can be obtained during pre-release testing. Historical study has at least two disadvantages. First, the historical record might be insufficiently accurate. For example, if one development organization records all identified defects while another records only defects discovered after unit testing, their defect counts might not be directly comparable. Second, much of the requisite data might not be publicly available.

Survey

One might assess a standard using a survey. For example, researchers could survey assessors to determine how broadly a given assurance requirement has been interpreted.

The advantages of survey research are that it is not constrained to available data like historical study, it is generally easier to plan and conduct than experimental research, and it can reveal important observations from people who work with standards professionally. But surveys have at least three disadvantages. First, it can be difficult to obtain a sufficiently high response rate from a representative sample of the target population. The responses of a few assessors

who decide to respond to a survey might not reflect the opinions of all assessors. Second, it is difficult to craft unbiased survey questions. The way a question is asked can easily skew responses. Third, surveys can only answer questions about what people know or think, which excludes many important questions. For example, opinions about the efficacy of achieving MC/DC might not reflect the actual efficacy of achieving MC/DC.

Experiments with Human Subjects

One might assess a standard using experiments featuring human subjects. For example, one could assess the efficacy of source code inspections (and how the inspection process affects this) by determining how many seeded defects subjects are able to locate [Ref. 41].

The advantage of experiments with human subjects is that they can answer questions about human performance — and thus about the efficacy of many development and analysis techniques — more definitively than historical studies because the experiments can control for confounding factors. But experiments with human subjects have at least three disadvantages. First, it is difficult to recruit a large representative sample of volunteer subjects. Easily recruited subjects such as students might not represent the population of interest, and practicing professionals are difficult to recruit. Second, the results might be difficult to generalize beyond the specimen problem or system used in the experiment. For example, skeptics might claim the results do not apply to their domain of interest because source code written for those applications has features not present in the code specimen used in the experiment. Third, the scope and scale of specimen artifacts and study process is typically limited by the need to conserve volunteers' time. For example, it would be difficult to recruit subjects willing to volunteer enough time to create a full-scale safety argument.

Suggestions Toward Assessment of a Standard for Software in Safety-Critical Applications

Our workshop discussions and subsequent thinking have prompted us to make several suggestions for assessing standards:

Provide Authoritative Definitions of “Works”

The assessment of standards is complicated at the outset by the need for (third-party) researchers to identify questions with answers that will support the decisions made about standards or based on conformance. If it is possible for standards committees — which ought to include some of the people making these decisions — to define what it means for their standards to “work,” they should. Where the definitions might vary with the circumstances of how standards are used, regulators who accept conformance could provide their own definitions.

Identify Data that Is Useful, Data that Is or Could Be Available, and Acceptable Anonymization

Historical studies are difficult, in part, because it is hard to identify relevant, available data. The AESSCS workshop was a first step toward addressing this difficulty, but securing access to needed data will require collaboration between the researchers conducting studies and the development organizations that have or must produce the data. Researchers could characterize data that would be useful so that developers know what might be of interest and can collect that data. Industry could identify the data it has or could collect and the conditions under which it would be willing to release that data to researchers. Data aggregation and anonymization techniques might be useful ways to address industry’s privacy and intellectual property concerns. It might help to have a trusted broker who could be given data to aggregate, anonymize and distribute to researchers in accordance with disclosure agreements.

Identify an Available Pool of Suitable Human Subjects

One of the chief difficulties of experimental research is recruiting suitable volunteers. Since research in fields such as psychology involves experiments on human subjects, many universities organize “human subjects pools,” and student experimenters typically volunteer as subjects in their peers’ experiments. If industrial developers of software for safety-critical applications value the results that could be obtained through experiments, a similar arrangement might be possible. Just as professionals donate time to review technical

manuscripts, development organizations might permit employees to donate time as study subjects. A central Website or mailing list might help match volunteers to studies, possibly with less bias than other methods.

Conclusions

The position papers submitted to *Planning the Unplanned Experiment: Assessing the Efficacy of Standards for Safety-Critical Software* (AESSCS 2014) and the resulting discussions revealed both important research challenges and subtleties that affect research design. Practical assessment of standards will require collaboration between academia, industry and regulators to define research hypotheses, identify available data, plan future data collection and recruit suitable study participants.

Based on these position papers, the workshop discussions and subsequent thinking, we have identified and discussed several candidate definitions of what it means for a standard to “work,” three potential evaluation targets, four assessment strategies and three types of research methods. One key observation is that there is no widely agreed-upon definition of what it means for a standard to “work.” Another is that no single assessment strategy or research method is perfect: Each has unique advantages and disadvantages. Building robust evidence that a given standard “works” will require several types of evidence addressing a mix of evaluation targets. The situation is analogous to software verification by testing: Developers perform a mix of unit testing, software integration testing, software testing and hardware-software integration testing because each addresses a weakness in the others.

“Further research is needed” is a cliché. Here, it is true. But performing that research will require first defining the right questions and then finding ways to provide the resources needed to answer them. Finding a practical way to gather useful research data while addressing the reasons industry is reluctant to disclose such data is one key part of that. Finding a way to recruit appropriate experimental subjects is another. We hope that by identifying these challenges and proposing concrete research ideas, AESSCS 2014 has moved the community closer to practical evaluation of the standards for software in safety-critical applications on which we all rely.

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