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A Real Options Approach to Testing

Part I: Challenges and Opportunities

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Abstract

Complex systems such as autonomous robots and networks of unmanned vehicles are being developed to perform sophisticated tasks and collaborative missions in uncertain operational environments. These systems may involve significant levels of autonomous behavior, may rely on network centric operations, or may constitute a system of systems (SoS) under the control of multiple independent stakeholders. Testing such complex systems presents unique challenges compared to traditional systems, especially given emergent behaviors and uncertainties surrounding anticipated missions and operations. In this paper, we discuss these challenges and their impact on a spectrum of test decisions, including test design, planning, execution, and long term strategy. We then show how real options methods can be applied to support decision making under uncertainty for testing complex systems.

Introduction

Inadequate testing of systems can lead to failures that may endanger human lives and result in catastrophic losses. Many techniques that focus on hardware and software testing have been developed to ensure test coverage and effectiveness. These techniques work well for systems that have well defined technical requirements and specifications. However, the advent of autonomous and networked systems that are expected to operate in system of systems environments has brought unique challenges to testing, such as dealing with increased complexity, greater extent of uncertainty, and emergent properties. Crucial test decisions must be made that can impact large scale operations of these systems. On the other hand, some properties of these systems may be leveraged to support testing efforts. In particular, robustness can emerge from flexibility; therefore, analysis of flexibility can inform testing under uncertainty. Test decision making should consider the impacts of uncertainty and flexibility, and leverage models to manage complexity.

Following a discussion of testing challenges for complex systems, we present a spectrum of relevant test decisions. We then discuss how real options identification and valuation methods can address a variety of test decisions.

Challenges in Testing Complex Systems

In this section we discuss three generic categories of complex systems and the testing challenges associated with each. The three categories are autonomous systems, network-centric systems and systems of systems. We then extract some common challenges that will be addressed in this paper.

1) Autonomous Systems Testing

Autonomous systems are typically characterized by some ability to intelligently perceive their environment, reason about goals, plan and execute tasks and actions without human intervention. Unlike traditional systems that are pre-programmed, autonomous systems may also exhibit more complex emergent behaviors such as assembling their own course of actions for a given mission goal, adapting to different environments, learning, diagnosing themselves and reconfiguring to maintain their functionality. Such autonomous capabilities may be enabled by novel algorithms and software without proven functionality. Since autonomous systems may not be subject to human control or frequent supervision, it is increasingly crucial to test and verify their capabilities, behaviors and ensure their safety.

The verification of software algorithms is a key aspect of testing autonomous systems, and at the system level it is important to consider potential interactions between the software and hardware components of the system, as well as their potential interactions with the external environment. Autonomous systems will have to operate in uncertain environments and the types of missions they may be required to accomplish may not be known in advance. Such sources of uncertainties, as well as the capability of the system to adapt in response to emerging needs must therefore be considered in testing autonomous systems.

2) Network-centric Systems Testing

Network-centric systems typically rely extensively on information received from the network for proper operation. A stand-alone system can operate independent of a network and therefore can be tested without consideration of interoperability issues. In contrast, a network-centric system is operationally dependent on a network, and/or it may in turn impact the operation of other nodes in the network. If a single node in the network, such as a network-centric vehicle, is to be tested, the rest of the network may be treated as an external environment. In that case, any interactions with the network may then be treated as external stimuli or constraints for testing the node. However, since network centric systems are interconnected and often operate collaboratively to accomplish a mission, testing a single node is not enough; the entire network operation must also be tested.

Testing of heterogeneous networks is especially challenging due to the prominence of interoperability issues. Of critical importance is the ability of the network to support the transmission of the correct information in a timely manner to the various systems involved in an operation. Therefore, testing network centric systems often encompasses testing conventional network properties, as well as emergent properties of the network and the ability of the networked systems to collaboratively accomplish a mission. For instance, the ability of the network to reconfigure in the case of a failed node in order to maintain connectivity to critical nodes is an example of an emergent property relevant to testing network-centric systems.

3) System of Systems Testing

A complex system under test may be a system of systems (SoS). This means that each of the systems that comprise the SoS is controlled or operated independently by a different stakeholder (for example, Army, Navy and Air Force). Constituent systems of a SoS may include autonomous and network centric systems described above. Again, if a single system is to be tested in the context of SoS, the rest of the SoS may be considered an external environment interacting with the system under test, as described in the previous section.

On the other hand, there is interest in testing an entire SoS which involves the integrated operation of different constituent systems from multiple organizations to accomplish more complex missions. This results in new and unique challenges for SoS testing [1], such as the added layer of complexity of dealing with stakeholders. Two associated challenges are as follows.

First, the system under test is no longer a technical system, but a socio-technical system that includes multiple stakeholders who impact the SoS operations. Testing the SoS (versus testing a system in a SoS environment) thus amounts to “testing” a socio-technical system or entire mission operations. Testing socio-technical systems can’t be based solely on technical performance criteria which may be ill-defined in this case. Therefore, mission level performance measures may augment conventional technical criteria. For example, the impact of limited stakeholder control over different networks within the SoS must be considered in evaluation of the SoS performance.

Second, the testing process itself must be carried out jointly across organizational boundaries with no single organization being responsible for the SoS performance. Joint testing introduces associated organizational challenges such as logistics, coordination and varying levels of stakeholder participation in joint planning and testing activities.

While dealing with the multi-stakeholder challenges constitutes the essence of testing SoS, there are also technical challenges that SoS testing inherits from its constituent autonomous and network centric systems. Examples of technical challenges include dealing with heterogeneous systems within the SoS and assuring their interoperability, testing the emergent properties of the SoS and dealing with uncertain operational environments and missions.

4) Common Challenges

Based on our discussion of challenges in testing autonomous systems, network-centric systems and SoS, we identify some common challenges to testing complex systems and discuss their implications. These challenges are as follows.

1. Complexity: Autonomous systems, network-centric systems and SoS are typically characterized by complexity, which is due partly to the sheer scale of these systems, as well as their myriad interdependencies and interactions with the operational environment. Furthermore, a SoS environment is characterized by boundaries of stakeholder control. Given such complexities, it is unlikely that a single analyst or tester will understand the entire system design and operations. This challenge in turn necessitates joint testing efforts and coordination among multiple system developers, testers and evaluators who understand different aspects of the system under test. Thus, complexity extends to the testing process as well. Joint modeling of the complexities of the system under test and/or the testing process may support better understanding of the dependencies and thereby support making better test decisions.

2. Uncertainty: There is significant uncertainty surrounding the development, testing and operation of complex systems. Uncertainty may exist in the system requirements, types of future missions, operational conditions and environments, the internal state of the system under test, or even in the testing process. Given limited testing resources, strategic testing decisions must therefore be made by considering relevant uncertainties. For example, test design decisions must consider the uncertainty in the operational scenarios for the SUT, while test resource investment decisions must consider uncertainty in the testing requirements and types of systems that may need to be tested in the long term.

3. Emergent Properties: Complex systems often exhibit emergent behavior, defined as high level behavior that is not pre-preprogrammed but rather results from the combined local actions of sub-elements of the system. A classical example is the swarming behavior of ants. Often, system level properties such as robustness and reconfiguration are considered to be emergent properties, because they emerge from lower level behaviors of sub-elements of a complex system. Testing of complex systems will have to consider emergent behaviors and properties.

   Given that uncertainties present a challenge to testing complex systems, in this paper we choose to focus on flexibility as a means of dealing with uncertainties to achieve system level robustness as an emergent property. In testing a complex system, the flexibility of the system to adapt must therefore be considered. For example, in the case of autonomous systems, flexibility may involve automated reconfiguration of components upon failure. In the case of network-centric systems, flexibility may involve rerouting information by leveraging node mobility. In the case of SoS, flexibility may involve switching to an alternative system to maintain mission level robustness in case a stakeholder withdraws their system from the SoS. These examples demonstrate that the flexibility of a system or SoS to adapt and thereby deal with uncertainties may impact its performance and effectiveness and is an important aspect of the test and evaluation of complex systems. Furthermore, flexibility is not limited to the system under test. Robustness can emerge from other types of flexibility, such as flexibility of the test process. For example, an adaptive test infrastructure enables testing different technologies within a SoS.

Motivated by the common challenges identified above, in the rest of this paper we tackle the problem of making testing decisions by considering uncertainties as well as flexibility as a means of managing uncertainties. We also propose tackling complexity by using a systematic model based approach to test decision making. As a first step, we discuss the types of testing decisions that we will address, and the impact of the above identified challenges on these testing decisions.

Test Decisions under Uncertainty

Test decisions may range in time scale from short term real time decisions such as the rate of data acquisition, to long term strategic decisions such as test infrastructure investments. In Figure 1, we present some generic categories of testing decisions mapped to an approximate time scale. Recall that the impact of uncertainties and flexibility on test decisions were two challenges identified above. For each test decision category in Figure 1, we provide an example of a specific decision under uncertainty. For each example, we also show how flexibility can help deal with uncertainty.

Note that testing decisions may not solely focus on the systems under test. For example, testing complex systems may require special test instrumentation or testing infrastructure and associated investment decisions. We therefore distinguish among decisions that directly relate to a specific system under test, such as test design, and decisions that relate to testing infrastructure or process. In either case, the challenges discussed above are applicable: uncertainty may impact any of the test decisions and flexibility should be considered as a means of managing uncertainty.

As shown in Figure 1, the long term decision category identified is strategic test decisions such as whether to invest in a new test technology or infrastructure. An uncertainty in this case may be whether new types of systems to be tested will emerge over the next five to ten years. If the test infrastructure is optimized for today’s testing needs, it may not be capable of supporting the test of future technologies. Flexibility in the test infrastructure may support its adaptation to new testing requirements. Therefore, flexibility is an important consideration for making long term strategic test investment decisions.

Shorter Horizon ⟵⟶ Longer Horizon

	Test Execution Decisions	Test Design Decisions	Test Planning Decisions	System Design Decisions	Strategic Investment Decisions
Decision	How much data to collect?	What to test?	What resources to allocate for testing?	Design for testability?	Invest in a testing infrastructure?
Uncertainty	Data corruption	Types of scenarios to be performed by SUT	Resource availability	Types of tests to be performed	Types of systems to be tested by the test infrastructure in the long term
Flexibility	Flexibility to adapt rate of data acquisition	Flexibility of the SUT enables robustness for multiple missions	Flexible test plans enable reverting to contingency resources	Flexibility of the system to integrate with different types of test equipment	Flexible test infrastructures enable handling multiple types of future systems

Figure 1: Examples of test decisions under uncertainty mapped to an approximate time scale. Flexibility is shown to provide a strategy for managing uncertainty in each case.

A second category of test decision identified in Figure 1 is system design decisions. System design decisions are longer term decisions from the testing standpoint since they occur early in the design phase of the system lifecycle. However, consideration of testing requirements is important since it may impact the testability of the system. An uncertainty in this case may be the types of data that testers will need to collect from a system. Depending on the type of data acquisition, different test instrumentation may need to integrate with the system. System design features that provide such flexibility, for instance through ports that may attach to various types of instrumentation, may outperform designs that are optimized regardless of testing requirements.

Third, we consider test planning decisions. Test planning may involve decisions that encompass capital budgeting, resource allocation, test scheduling and logistics. For example, a decision maker may need to allocate resources to a system test event. There may be uncertainty regarding the availability of a specific resource, especially in the case of a joint system of systems testing that has challenges in coordinating multiple stakeholders and their respective constraints. Consideration of flexibility in test planning will ensure adequate contingency planning.

Fourth, we consider test design decisions. Test design relates more closely to the system under test since it involves decisions around what aspects of the system to test and what types of inputs to prescribe for testing. Such testing decisions involve uncertainty because often the potential types of missions that will rely on the system may not be known in advance. Identification of the flexibility of the system under test is important in this case and can provide insight on how robustness emerges from flexibility and where to focus the testing effort.

We also consider real time decisions that have a rather short horizon, such as those that relate to test execution. An example is how much data to acquire during testing given the likelihood that the collected data may be corrupt. Flexibility to adapt the testing by adjusting the rate of data acquisition or extending the test duration may provide means of managing such uncertainty.

The examples presented in this section are meant to be representative of the types of test decisions under uncertainty and are also meant to demonstrate the role of flexibility consideration in test decisions. We do not claim that the categories of decisions are exhaustive. In general, testing decisions may involve addressing the what, why, when, where, who, how and how much of testing. Some of the categories in Figure 1 capture those questions. For example, how to enable testing is associated with decisions on strategic infrastructure investments, and system design for testability decisions. What to test is relevant to test design decisions, whereas the when, where and who are relevant to test planning decisions.

In the rest of this paper, we present the real options approach as a foundation for making test decisions under uncertainty through the identification and valuation of flexibility.

Real Options

While consideration of flexibility is important, flexibility may not always be worthwhile. Valuation of flexibility involves quantitative analysis to determine whether embedded flexibility to manage uncertainty makes a specific decision worthwhile. Traditional valuation methods used for capital investment decision making, such as the discounted cash flow, do not consider the role of flexibility. Real options analysis (ROA) [2, 3] is an alternative method that has supported decision making under uncertainty by considering flexibility in the context of numerous applications. While initial applications involved valuation of capital budgeting decisions [4] such as IT investments [5], valuation of R&D [6] and intellectual property [7], applications have expanded to include valuation of system designs under uncertainty [8, 9]. In this paper, we further expand the application domain by introducing a real options approach to test decisions.

The term real option [10] is commonly defined as the right, but not the obligation, to take an action in the future, and thus it's been associated with the concept of flexibility. Each of the examples of flexibility in Figure 1 corresponds to a type of real option, i.e. a specific type of action that may be executed in the future. An example of a real option in the testing process is the action to switch to using a different test resource when a contingency arises. The real option to switch resources is a right but not an obligation, because one has the option to switch when specific circumstances arise.

Real options analysis involves the identification of real options, the valuation of real options, or both. Real options valuation was described above as a method that incorporates the value of flexibility in decision making under uncertainty. On the other hand, real options identification involves determining what flexibility, if any, exists (or may be introduced) for managing uncertainty. This information can be used for valuation purposes, but also for other types of potential analyses or algorithms which can leverage the identified flexibilities.

Identification of real options is often done in an ad hoc manner. This generally works well for simple cases that involve a small knowledge base. To tackle the challenge of complex systems that typically involve multiple interactions or dependencies, more systematic methods of identifying flexibilities must be leveraged. In prior work [11], we introduced an approach for model based identification of real options. This approach involves the construction and use of a logical coupled dependency structure matrix (CDSM) model. In [11], besides identifying the *types* of flexibility, i.e. the types of real options that can manage uncertainties, we also identified the *mechanisms* that enable flexibility, referred to as real option mechanisms. For each example of flexibility presented in Figure 1, a specific mechanism that enables the corresponding real option can be identified. For instance, the option to switch to an alternative resource is enabled by the mechanism of purchasing or scheduling a contingency resource at additional expense.

Real Options for Test Decisions

In this section, we introduce a real options approach to making test decisions under uncertainty for complex systems. We show how real options identification and real options valuation methods described above can be leveraged for different types of test decisions.

1) Real Options Identification

We start by exploring the potential uses of real options identification. In particular, we distinguish among the identification of mechanisms (enablers) and types (resultant actions that manage uncertainty) of real options. As described in [11], a motivation for this distinction is that the mechanism and type are not necessarily collocated. We show this in the testing context by considering two relevant dimensions: the system under test (SUT) and the testing domain. The quadrant in Figure 2 shows that each of the mechanism and type may exist in the SUT or the test domain. Note that in Figure 2, the system refers to a generic SUT and by “design” we do not solely refer to a technical design of the SUT; the term design may encompass design of operations, because the SUT may be a system of systems or a network-centric system in the context of operational testing. Similarly, the test domain is quite generic and may include developmental testing, integration testing, operational testing or test designs.

Combinations of mechanisms and types in each of the system and test domains result in four categories of analysis as follows.

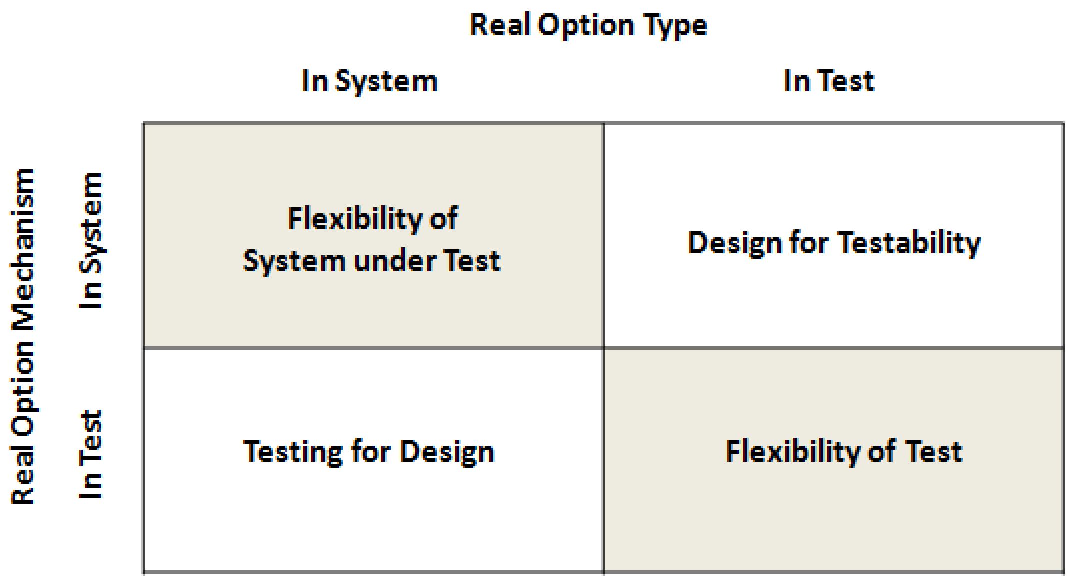

Figure 2: Real options identification quadrant showing that mechanisms and types of real options can be identified in the system (under test) and the testing domain. The shaded cells represent single-domain flexibility, whereas the white cells represent flexibility of interactions among testing and system design.

1. Flexibility of the SUT: This refers to the case where the both the mechanism and type of real option are in the SUT. The idea here is to analyze the design and operations of the SUT in order to identify the mechanisms and types, which provide information on whether and how the SUT deals with uncertainties. Identification of the SUT flexibilities can then be used to support test design decisions. An example is a switch mechanism within a robotic SUT design that enables the option to switch to a secondary camera upon encountering a failure of the primary camera. Another example is a modular payload system onboard a vehicle that enables the option to switch payloads to perform different missions. By identifying where are the SUT flexibilities, insight can be obtained on how robustness is achieved as an emergent property, thereby supporting the design of relevant test scenarios. Relevant questions associated with this category of analysis include: 1) which design features of a system under test enable dealing with operational uncertainty in a SoS environment? 2) How does this knowledge help in test design, i.e. what to test?

2. Design for Testability: In this case, mechanisms in the system design enable real options in testing. In terms of real options identification, the idea is to analyze the SUT in order to identify design mechanisms that provide testing options. For example, a data recorder onboard the SUT enables an option to leverage this data for testing. Relevant questions associated with this category of analysis include: 1) which features of the

system under test enable testability? 2) What types of tests do they enable? 3) How does this knowledge support decisions on how to test the SUT?

Note that both categories described above, Flexibility of the SUT and Design for Testability, are represented in the first row of the quadrant in Figure 2, since in both cases the mechanism is within the system. Therefore, both approaches involve analysis of the SUT (design, capability, operations). In the first case, the results may support decisions on what to test, whereas in the second case they may support decisions on how to test.

3. Testing for Design: In this case, which may be considered a reverse parallel of design for testability, testing mechanisms enable real options for the system design, which can encompass operations design. For example, conducting a proof of concept test that enables an option to incorporate a new design feature into the system, or an operational test that increases the confidence in a specific scenario, thereby enabling an option to execute that scenario in a future mission. Relevant questions associated with this category of analysis include: 1) which tests enable design options for future systems? 2) Which tests enable deployment of new operational scenarios? 3) What types of features and operations can be enabled by testing?

4. Flexibility of Test: The categories discussed above so far all involve some analysis of the SUT in order to support test decisions. Flexibility of Test is the case of both the mechanism and type of option being within the test domain which encompasses the spectrum of test decisions from strategic investments to test design, planning and execution. Therefore this analysis does not directly involve the SUT. For example, investment in a test technology is a mechanism that enables the option for a new type of testing. Another example is staged or incremental testing as a mechanism that enables the option to expand testing as needed. Relevant questions associated with this category of analysis include: 1) how does developmental testing enable options for operational testing? 2) What mechanisms enable options for adaptive testing?

While in the above discussion we focused on how the identification of mechanisms and types of real options can provide information to support various testing decisions, we did not specify a particular method of identifying the real options. Most complex systems under test have many dependencies within and external to the system. Therefore, a systematic method such as the one described in [11] can be used for modeling and identifying the real options for such systems.

2) Real Options Valuation

We now shift to exploring the applications of real options valuation (ROV) to test decisions under uncertainty. Real options valuation is one potential way to leverage the identified mechanisms and types of real options for making test decisions under uncertainty. However, real options valuation is not limited to valuation of real options identified in retrospect—it can also be used to value the synthesis of new options that can be embedded to manage uncertainties. Next, we describe how the categories identified in the Figure 2 quadrant can relate to real options valuation.

1. Flexibility of the SUT: The real options identified in this category represent the flexibilities of the SUT that have been identified in retrospect, i.e. by analyzing an existing SUT. On the other hand, valuation of the SUT flexibility is helpful for deciding what new options to embed in the system during the initial design phase, when system design decisions under uncertainty are being made. This phase does not directly involve test decisions. However, it is still relevant to testing, if the system flexibility is designed to manage a testing uncertainty. For example, if there is uncertainty as to whether testing will or can be performed for a specific component, a modular system may be designed to enable the option to switch to a different component that has been previously tested. Applications of ROV to system design decisions have been described in the literature. Whereas ROV can provide a prescription to system design decisions, the identification of the SUT flexibilities provides knowledge that may be used in conjunction with other algorithms designed to prescribe what to test.

2. Design for Testability: Recall that the identification of existing design for testability options as discussed earlier is relevant to identifying how to test a system. On the other hand, real options valuation can be applied to make design for testability decisions under uncertainty. The latter occurs in the system design phase, when testability should be a relevant consideration in the system's design. Unlike the flexibility of the SUT category, design for testability directly enables real options for testing. Design for testability includes the case of a flexible SUT design that enables test options. A relevant question that can be addressed through ROV in this category is: which system design features (mechanisms) that enable testability are most valuable given uncertainty in testing priorities? ROV helps determine whether system designs that enable test flexibility are worthwhile in this case.

3. Testing for Design: Real options valuation can be applied to value test designs or plans in terms of their capability to enable system design or operation. Therefore, a relevant testing question that can be addressed is: which test designs are valuable in terms of enabling future system design features given uncertainty in system requirements?

4. Flexibility of Test: The real options identified in this category may be used in conjunction with real options valuation to make testing decisions under uncertainty. For example, test infrastructure investments can be valued by considering their flexibility to manage uncertainty in future test requirements. Test plans and resource allocation strategies can be valued in terms of their flexibility to respond to contingencies. Test designs can be valued in terms of their flexibility to manage uncertainty in testing requirements or their flexibility to test different types of system designs. Therefore, a relevant question that can be addressed here is: Is flexibility in test design/planning/execution valuable under various kinds of uncertainty?

Note that in all of the applications described so far, we have localized the mechanisms and types of real options. It is also possible to localize the uncertainties. Sources of uncertainty are not limited to the system or test domains. For example, a source of uncertainty may be the environment in which the system will operate.

In Figure 3, we summarize the applications of real options identification and real options valuation to various testing decisions. In comparing the two approaches and their respective applications, keep in mind that real options identification as described here involves analysis of an existing system for the purpose of capturing knowledge to support methods for prescriptive decision making, whereas real options valuation can directly support prescriptive decision making under uncertainty.

Conclusion

We have presented challenges to testing three types of complex systems: autonomous systems, network-centric systems and system of systems. Three common challenges were identified and opportunities for addressing them were presented in this paper. The first challenge is the complexity of both the system and the test. The second is the uncertainty surrounding various testing decisions. The third is emergent properties which are often the result of local mechanisms and interactions, such as achieving robustness through flexibility. We identified flexibility and its enabling mechanisms to be important considerations for test decisions. Furthermore, flexibility is not limited to the system under test, but can encompass both the system and testing domains to cope with uncertainties. We then presented a spectrum of testing decisions under uncertainty that may benefit from consideration of flexibility.

While real options have been used for decision making in a variety of contexts, the extent of its applicability to testing decisions had not been previously explored. We showed how the real options approach, which encompasses the identification and valuation of real options, can be applied to different testing decisions that were identified. We also proposed to address complexity by constructing models that can be leveraged by the real options methods. Future work will explore how the approaches described in this paper can be implemented, and demonstrate the application of specific approaches to representative scenarios and testing decisions.

	Real Options Identification	Real Options Valuation
1. Flexibility of SUT	Approach: What real options are available for the SUT and what mechanisms enable them? ⇨ Decision: What to test given the flexibilities of the SUT?	Approach: What is the value of a system design that enables real options? ⇨ Decision: Is a flexible system design worthwhile under testing uncertainty?
2. Design for Testability	Approach: What real options for testability are available for the SUT and what mechanisms enable them? ⇨ Decision: How to test given the SUT design?	Approach: What is the value of a system design that enables real options for testability? ⇨ Decision: Is a system design that enables testability worthwhile under uncertainty?
3. Testing for Design	Approach: What test mechanisms enable real options for system design and operations, and what types of real options? ⇨ Decision: Which test designs enable potential future capabilities?	Approach: What is the value of a test that enables real options for system design and operations? ⇨ Decision: Is a test worthwhile in terms of its potential to enable future capabilities?
4. Flexibility of Test	Approach: What real options are available for testing and what test mechanisms enable them? ⇨ Decision: How does test flexibility enable managing uncertainty?	Approach: What is the value of a test decision that enables real options for testing? ⇨ Decision: Is a flexible test strategy worthwhile under uncertainty?

Figure 3: Real options identification and valuation approaches to a spectrum of test decisions.

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