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Real Options in Enterprise Architecture: A Holistic Mapping of Mechanisms and Types for Uncertainty Management

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Abstract—Uncertainty management is crucial for achieving high performance in enterprises that develop or operate complex engineering systems. This study focuses on flexibility as a means of managing uncertainties and builds upon real options analysis (ROA) that provides a foundation for quantifying the value of flexibility. ROA has found widespread applications ranging from strategic investments to product design. However, these applications are often isolated to specific domains. Furthermore, ROA is focused on valuation, rather than the identification of real options. In this paper, we introduce a framework for holistic consideration of real options in an enterprise context. First, to enable a holistic approach, we use a generalized enterprise architecture framework that considers eight views: strategy, policy, organization, process, product, service, knowledge, and information technology (IT). This expands upon the classical IT-centric view of enterprise architecture. Second, we characterize a real option as a *mechanism* and *type*. This characterization disambiguates among mechanisms that enable flexibility and types of flexibility to manage uncertainties. Third, we propose mapping of mechanisms and types to the enterprise architecture views. We leverage this mapping in an integrated real options framework and demonstrate its benefit over the traditional localized approach to ROA.

Index Terms—Decision making, enterprise architecture, flexibility, real options, uncertainty management.

I. CHALLENGES AND APPROACH

COMPLEX systems are developed and operated by complex enterprises that are, in turn, subject to uncertainties. Management of uncertainties facing complex enterprises is crucial for achieving high performance for the enterprises as well as the systems that they develop and operate. The recent economic recession and its impact on the automotive industry is an example of negative consequences on enterprises that cannot manage uncertainties. Catastrophic failures, such as the Space Shuttle Columbia accident, have suggested that failures exhibited at the engineering-design level may be rooted at the organizational level [1]. This motivates research on uncertainty and risk management in an enterprise context.

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Uncertainties may be managed through flexibility, which has been modeled and valued using real options analysis (ROA) [2]–[4]. A real option gives the decision maker the right, but not the obligation, to exercise an action or decision at a later time. For example, the ability of a spacecraft to reconfigure upon failure by exercising the real option to switch to redundant components is one form of flexibility. The ability of an organization to exercise the real option to expand a project upon increasing demand by shifting its resources is another example of flexibility. In each of these cases, a real option is provided through an initial investment that is later leveraged to deal with uncertainty as it unfolds. In the spacecraft case, the design decision incorporates redundancy as a mechanism to deal with failures. In the case of the organization, the project investment decision incorporates a plan for mobilizing project resources as a mechanism to deal with changing demand.

ROA has traditionally been applied to value business investment decisions under uncertainty [3]–[5] by taking into account managerial flexibility. More recently, ROA has been applied to value system design flexibility [6]–[8]. However, ROA is applied to these different domains in isolation, and focuses on valuation rather than the identification of real options. The problem addressed in this paper is how to enable a holistic real options approach to managing uncertainty in an enterprise context. Besides valuation, the identification of existing and potential real options is an important enabler. In particular, the following two challenges are addressed.

- 1) Although ROA is applied to different domains relevant to an enterprise, there is no integrated framework that enables systematic identification and subsequent valuation of: a) what type of flexibility is desirable to manage uncertainty? b) how to enable such flexibility? and c) where to implement flexibility in an enterprise?
- 2) Enterprises often exhibit the emergence of isolated silos over time as complexity grows [9]. This may result in local optimization as decision makers exercise independent decentralized control within their specialized division. For instance, real options considered within isolated technical versus strategic silos may lead to suboptimal means of implementing flexibility.

Our approach is to first enable holistic thinking through a new enterprise architecture framework that encompasses eight views: strategy, policy, organization, process, product, service, knowledge and information technology (IT). Real options identification should cross the boundaries of enterprise silos by considering dependencies both within and among the multiple

enterprise views. We then introduce a new real options characterization that distinguishes between the enabling mechanisms and types of real options for managing uncertainty. We show how this characterization provides an overarching model for the disparate applications of real options in prior work. Whereas prior work has focused on the classification of types of options, we show that it is also possible to classify patterns of mechanisms that enable real options. We explore the relations among the mechanisms and types of real options and present their mapping to the enterprise architecture. Finally, we apply these concepts within an integrated real options framework (IRF) and demonstrate the benefit of holistic consideration of real options through application to a surveillance mission.

II. ENTERPRISE ARCHITECTURE

In this section, we discuss limitations of prior work in enterprise architecture frameworks and present a holistic enterprise architecture framework that we will use in this study.

A. Overview of Enterprise Architecture Frameworks

Enterprise architecture frameworks have been developed and used in enterprise IT system implementations [10]. A recent survey of enterprise architecture trends revealed statistics on the usage of enterprise architecture frameworks [11]. The most popular frameworks include the Zachman Framework [12] (25% usage based on surveyed organizations), The Open Group Architecture Framework (TOGAF) [13] (11%), the DoD Architecture Framework (DoDAF) [14] (11%), and the Federal Enterprise Architecture Framework (FEAF) [15] (9%). Around 22% of surveyed organizations were found to use custom enterprise architecture frameworks.

What is common to most enterprise architecture frameworks is that they represent the information architecture of the enterprise, with limited modeling of other aspects such as the technical architecture of products developed by the enterprise. While the DoDAF includes operational, systems and technical views that also document the technical system in detail, prior work [16] has shown that dependencies among the views in DoDAF are not fully captured.

B. Eight Views of Enterprise Architecture

The importance of IT in supporting decision making processes has led to the frequent association of enterprise architecture with the IT architecture for the enterprise [17]. However, since enterprises are complex socio-technical systems, it has been proposed that system architecture principles can be extended to the architecture of enterprises [18], [19]. Nightingale and Rhodes refer to enterprise architecture more generally as the structure and behavior of an enterprise, and thus define enterprise architecting as [20] “*Applying holistic thinking to design, evaluate and select a preferred structure for a future state enterprise to realize its value proposition and desired behaviors.*” They report [19], [21], [22] that enterprises are often viewed through specific and narrow views. Examples include the IT view that focuses on the IT architecture as the foundation for

TABLE I
ENTERPRISE ARCHITECTURE VIEWS

Strategy	The goals, vision, and direction of the enterprise, including the business model and competitive environment.
Policy	The external regulatory, political and societal environments in which the enterprise operates, as well as policies internal to the enterprise.
Organization	The organizational structure, as well as the relationships, culture, behaviors, and boundaries between individuals, teams and organizations.
Process	The core, enabling and leadership processes by which the enterprise creates value for its stakeholders.
Product	The product architectures of the enterprise.
Service	The architecture of the services of the enterprise, including service as a primary objective or in support of products.
Knowledge	The implicit and tacit knowledge, capabilities, intellectual property resident in the enterprise.
IT	The information needs of the enterprise including the flows of information as well as the systems and technologies needed to ensure information availability.

the enterprise [10], [17], the process reengineering view of enterprise architecture [23], and the organizational transformation view [24].

In order to support a holistic approach to enterprise architecting as defined above, Nightingale and Rhodes proposed a new framework [21], [22] that integrates the different views used to describe enterprise architectures. The eight views are strategy, policy, organization, process, product, service, knowledge, and IT. Each of the views is described in Table I. Nightingale and Rhodes converged to these views through insights gained by case studies [22] in multiple industries, and by identifying the multiple lenses through which enterprises have been studied within the management literature. Dependencies may exist both within and among the views. For example, organizational structure reflected through the organization’s stakeholders and partnerships is influenced by strategic objectives such as offering a product in a new market.

The eight views framework provides a holistic and structured way to think about information relevant to modeling an enterprise. It also extends the IT centric view of enterprise architecture to encompass other views such as policies and products. While the real options concepts developed in this paper are applicable to other multi-domain frameworks, in the following sections we leverage these eight views of enterprise architecture for holistic mapping of real options.

III. REAL OPTIONS: CONCEPT AND APPLICATIONS

Real options emerged from the motivation to apply financial options theory to capital investment decisions [2]–[4]. As such, research on real options has been focused on valuation. In this section we present a critical analysis of the concept and applications of real options and identify some limitations.

A. Definition

The term real options was first used by Myers [2] in the context of strategic decision making. The word real refers to the fact that the underlying asset is real rather than financial. The goal of ROA is to value decisions under uncertainty by taking into account the options that are available to the decision maker in the future. For instance, the ability to abandon a project or expand an investment in the future are two types of real options that must be taken into account when valuing the decisions of whether to invest. Real options encompass the management of both risks and opportunities that arise due to uncertainty.

A real option is generally defined as “the right, but not the obligation, to take an action at a future time.” At an intuitive level, real options capture the idea of flexibility. However, the definition of real options is more elusive than that of financial options. For example, the use of the term “right” in the definition of the real option is controversial because there is not necessarily a legal contract that enforces the ability to exercise the future action, in contrast with the case of financial options where the option is acquired by purchasing a contract. This motivates a new formulation in this paper that explicitly characterizes how the real option is acquired or enabled. Another difference is that a financial option has a clearly defined action which is to buy or sell stock, whereas that *action* is unspecified in the real option definition.

Ambiguity in the real option concept has resulted in alternative interpretations and applications that we discuss further in Section III-C, following a brief background on real options valuation.

B. Real Options Valuation

The traditional method of valuing capital investment decisions is the discounted cash flow (DCF) analysis. DCF analysis is based on discounting the cash flow to adjust for the time value of money. In order to account for riskier investment using DCF analysis, the discount rate is adjusted to be higher. In contrast, ROA considers future actions that can be taken to manage uncertainties by either limiting risk or taking advantage of opportunities.

Valuation methods that have been used for ROA include Black–Scholes, binomial lattice valuation, and Monte Carlo simulation. The Black–Scholes model [25], [26] is an analytical formula for pricing a special case of options that can only be exercised on a specified date. As such, it does not translate well to real options that typically can be exercised within a window of opportunity. The binomial lattice model [27] is a practical method that models uncertainties and outcomes at discrete time steps. Each node in the lattice leads to two others representing up and down movements at the next time step, such that values at later nodes are modeled as multiples of earlier nodes. Dynamic programming is then used to recursively calculate the option value at each node of the lattice, starting at the end and discounting the values to the present time. We use the binomial lattice for the example case in Section VIII-B. Monte Carlo simulation [28] estimates the expected value of the option by simulating thousands of potential scenarios for uncertain vari-

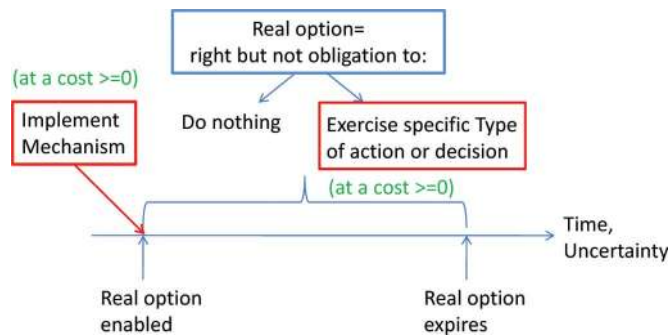


Fig. 1. Anatomy of a real option.

ables. It is typically used for cases involving multiple sources of uncertainty.

C. Applications

According to the definition of real options, any action that can be taken in the future can be considered to be a real option, as long as it presents a right but not an obligation. This has led to nontraditional application of real options, such as the valuation of system designs, in terms of future actions that they enable. A distinction has been drawn between 1) real options “on” projects [3], [29], [30], which refer to managerial flexibility in making strategic decisions regarding project investments, and 2) real options “in” projects [6], [8], [31], which refer to engineering design decisions that enable the flexibility to change the system in the future. While real options in design are considered to be the domain of engineers, real options on projects are considered to be the domain of managerial decision makers. This hinders a holistic approach, since ignoring the consideration of real options outside of each silo may lead to suboptimal means of managing uncertainty within enterprises.

Furthermore, an important distinction is the alternative interpretations of real options. Classical ROA focuses on analysis, where the idea is to consider the impact of the flexibility to exercise future actions on current decisions. In the case of real options in projects, the idea is to actively design systems that enable flexibility in the future. This latter application can be interpreted as real options synthesis rather than analysis. The real options in design are enablers of flexibility in this case rather than the future flexibility.

IV. CHARACTERIZATION OF A REAL OPTION

We introduce a new characterization of a real option that distinguishes among the enablers and types of real options, in order to encompass the alternative interpretations and uses of real options and associated terminology. Fig. 1 shows the proposed characterization of a real option, consisting of the following.

- 1) *Mechanism*: A mechanism is defined as an action, decision or entity that enables a real option. The mechanism can therefore be interpreted as a source of flexibility. For example, designing a modular payload bay for an unmanned aerial vehicle (UAV) is a mechanism that enables the real option to switch the type of payload; reserve funding is a

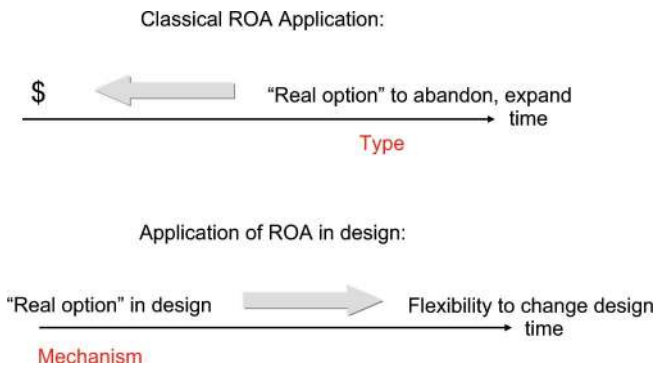


Fig. 2. Reconciling the uses of the “Real Option” terminology.

mechanism that enables the real option to buy a plant to expand productive capacity.

- 2) *Type of real option*: A real option type refers to an action or decision that may be exercised by the owner of the real option. The type is therefore representative of the future flexibility. For example, the option to switch the payload of a UAV and the option to purchase an additional plant are different types of options, referred to as switching and expansion options respectively.

This new conceptualization identifies that there are two distinct sets of entities that relate to real options. One is the mechanism that enables a real option, and the second is the type of the real option. Therefore, a real option can be characterized as a tuple $\langle \text{Mechanism, Type} \rangle$. For example, a modular UAV payload bay enables flexibility to use the UAV for a variety of missions. This real option can be characterized by the tuple $\langle \text{Design modular payload bay, option to switch to different payload} \rangle$ for managing uncertainty in mission demand. As shown in Fig. 1, implementing a mechanism enables a real option that may have an expiration date. The type of real option may be exercised before the expiration date of the option, as uncertainty is resolved in the future. Note that it is possible for types of real options to also be mechanisms that enable other types of options. This corresponds to a chain of real options which is discussed later in Section V (see Fig. 6). For example, the modular UAV payload-bay design enables the option to switch to an infrared camera payload for nighttime imaging, which, in turn, enables the option to switch to an autonomous nighttime navigation mode.

Fig. 2 shows how the proposed distinction among the mechanism and type reconciles the various uses of the real option terminology. In the classical application of ROA, the real option is used to describe the right but not the obligation to take a future action, which is then considered in the valuation of decisions under uncertainty. On the other hand, in engineering applications that actively synthesize options, the term real options is typically used to refer to a design feature that enables some flexibility. In this latter context, the real option refers to the source of flexibility rather than the flexibility, which renders the use of the term “real option” ambiguous. These two applications use real options in two different frames of reference, which is a manifestation of the silo effect. Furthermore, the term has been used as a shorthand for real options analysis.

		Real Option Type	
		In	On
Real Option Mechanism	In	MAV design enables a reuse option in future design	MAV design enables future market expansion
	On	MAV development partnership enables option to use new type of technology in design	Investment in MAV project enables option to expand development to swarm in future

Fig. 3. Real-option mechanism and type may exist in and on projects. An example of each combination is given for an MAV project.

The proposed characterization of a real option disambiguates the various uses of “real options” by locating both the mechanism and type in a single frame of reference. The classical ROA is shown to be focused on types of real options, that is, future actions, while the real options in design is shown to be focused on mechanisms that enable future actions. In order to support the classical ROA, prior work has focused on documenting different types of real options, such as the options to defer, abandon, switch, expand and contract [3], [4]. However, the identification and implementation of mechanisms are increasingly important in efforts to actively seek flexibility for managing uncertainties. We present examples of patterns of mechanisms in Section VII.

A. Reinterpretation of Real Options On and In Projects

As discussed in Section III-C, prior work has made a distinction between real options in and on projects. However, one of the findings of this research is that this dichotomy can be ambiguous, because it does not specify whether it is the mechanism or the type of real option that is “in” or “on” the project. This is demonstrated below with an example.

Fig. 3 shows a matrix of possible combinations of mechanisms and types of real options in and on a project. An example is given for each combination of mechanism and type of real option for a mini air vehicle (MAV) project. A mechanism in the project is a design feature that enables real options. The resulting type of real option may be in the project, such as the option to reuse the design. A design mechanism may also enable a real option in strategy, which is an example of a real option on a project. The example given is a design feature that enables the option to expand the market size by making the MAV function appealing to a different set of customers. An example of a mechanism on a project is a strategic partnership. A mechanism on a project may enable a real option in design. For example, the strategic partnership may provide the opportunity to leverage a new technology developed by the partner organization in the MAV design. Finally, an example of a mechanism on the project that enables a real option on the project is the decision to invest in a MAV project that, in turn, enables the option to expand this project later to a swarm of MAVs.

The MAV examples indicate that it is possible to classify the “location” (in this case the location is either in or on the project)

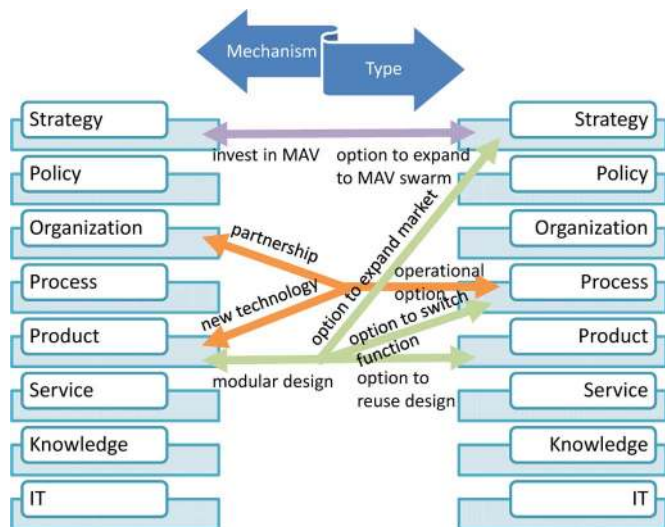


Fig. 4. Some examples of mapping of real-option mechanisms and types to enterprise views.

of both the mechanism and type of a real option. The question of where to insert real options in a system or project [16], [31] has been investigated in recent research. Given the new $\langle \text{Mechanism, Type} \rangle$ characterization of a real option, it can be seen that the question of where to insert real options consists of two distinct questions. The first is where to insert the type of real option, that is what type of flexibility is desirable. The second is where to insert the mechanism of the real option, that is how to enable the flexibility. An important implication of the new model of real options is that different combinations of locations of mechanisms and types may systematically be explored to deal with uncertainties. For example, ROA will traditionally not have considered a strategic partnership as a mechanism on the project that enables a real option in system design (see Fig. 3), whereas the new classification enables the explicit consideration of such an option. In the following section, we expand the mapping of real options mechanisms and types from in and on projects to the enterprise architecture.

V. MAPPING OF MECHANISMS AND TYPES TO ENTERPRISE VIEWS

We present a framework for holistic consideration of real options in enterprise architecture by leveraging the enterprise views introduced in Section II and the $\langle \text{Mechanism, Type} \rangle$ characterization of a real option introduced in Section IV. We develop a theoretical mapping of mechanisms and types of real options to the enterprise views. We also show that this mapping encompasses special cases of real options.

Fig. 4 shows some examples of real options mapped to enterprise views. This mapping enables systematic identification, documentation and exploration of existing and new combinations of mechanisms and types of flexibility across enterprise views. A key insight is that for a tuple $\langle \text{Mechanism, Type} \rangle$, each of the mechanism and type may exist within any of views of an enterprise. As shown in Fig. 4, a modular design (product view) can enable: 1) the option of component reuse in a future

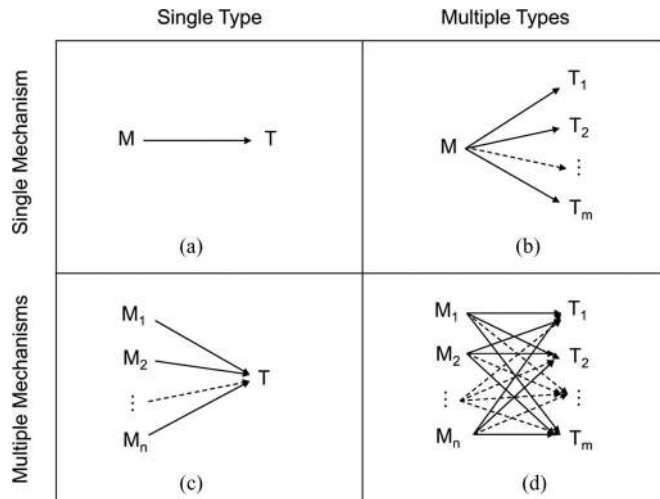


Fig. 5. Relations between mechanisms and types of real options.

design, 2) the option to provide a different function during system operation, and 3) the option of customization for market expansion. In this example, the mechanism is implemented in the product, and the real options are enabled in the product, operational process, and strategy views, respectively. Therefore, a single mechanism can enable multiple types of real options in possibly multiple views of the enterprise.

It is also possible to have a compound mechanism, whereby a set of entities is required to enable a type of option. The mechanisms in this case may be distributed across different enterprise views. For example, a partnership (organization view) and a new technology (product view) may be necessary to enable an operational option (process view). This concept of compound mechanism is consistent with the definition of a complex real option in [32, p. 63], which was motivated by the need to consider enterprise level issues in implementing a real option:

“A complex real option is composed of multiple components across a variety of dimensions, such as technical, financial, political, organizational and legal. All components are necessary for the option to be deployed and exercised; no single component is sufficient.”

The complex real option in this definition refers to a set of mechanisms $\{M_1, M_2, \dots, M_n\}$, where each mechanism M_i , $i = 1 \dots n$ is located in any of the enterprise views, and where no single M_i is sufficient to enable the type of option. We will revisit this as a special case of the theory introduced below.

We introduce a generalized mapping of the mechanisms and types of real options to enterprise views. In the context of the enterprise views, mechanisms and types of real options can be defined as sets $M = \{M_i\}, i = 1 \dots n$ and $T = \{T_j\}, j = 1 \dots m$ where each M_i and T_j is mapped to an enterprise view. Relations between mechanisms and types of options across the enterprise views can then be generalized, as shown by the 2×2 matrix in Fig. 5. The following discussion provides case examples for the various combinations.

- 1) Case (a) is a base case ($i = 1$ and $j = 1$), where a single mechanism enables a single type of option. The mechanism and type may each exist in any of the enterprise

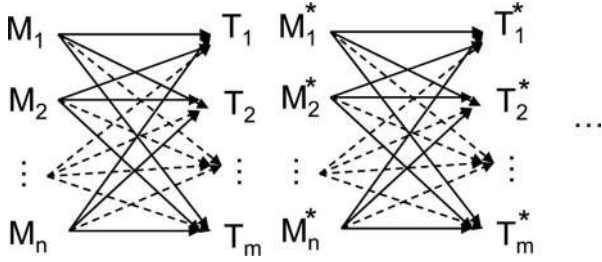


Fig. 6. General case of compound options as chain of mechanisms and types.

views. For example, reserving slack funding resources (strategy view) enables the allocation of additional funds to a specific project with cost overruns (process view).

- 2) In case (b), a single mechanism ($i = 1$) enables multiple types of options. For example, cross training of employees (knowledge view) enables the option to assign them to a number of different departments and projects for which they are trained (organization view).
- 3) Case (c) is that of multiple mechanisms that enable a single type of option ($j = 1$). A specific example of this case presented in [32] is from the Intelligent Transportation Systems (ITS) domain, where two mechanisms: an ITS solution (product view) and training of transportation organizations to operate the new ITS capability (organization view) were both required to enable the option to actively manage road networks and lanes (process view). Note that in this example, all the mechanisms must be implemented to enable the option. This is a restrictive case that is expanded in this paper to encompass the case where alternative multiple mechanisms that enable the same type of option may also exist. For example, the option to actively manage the roads can alternatively be enabled by another compound mechanism that involves: 1) deployment of a completely automated ITS system (product view), assuming that such a system exists, and 2) introduction of a policy that allows for autonomous operation of the ITS (policy view). Note that the representation in Fig. 5(c) does not explicitly convey the logical distinction between multiple required mechanisms and alternative mechanisms.
- 4) Case (d) is the more general case where multiple mechanisms enable multiple types of real options across multiple enterprise views. Building upon the example from ITS in case (c), the implementation of the compound mechanism: 1) deployment of ITS solution with autonomous operation capability (product view) and 2) training of transportation organizations (organization view) will enable not only 1) the option to manage the road network by the organizations (process view), but also 2) the option to switch to autonomous operation mode (process view).
- 5) Finally, the cases can be generalized as shown in Fig. 6 to represent a compound option that is defined in the literature as an option *on* an option. A compound option can be thought of as a chain of mechanisms and types, where each type of option serves as a mechanism that enables further types of options. For example, staged investments can be modeled as compound options. An initial investment

	Mechanism that enables real option	Type of real option
Strategy	Invest in university research Joint venture Reserve slack funds	Expand collaboration Charge customers for module upgrades
Policy	Policy on Internships Formulation of bankruptcy law Policy on IT security & privacy	Declare bankruptcy
Organization	Partnership	Full time hiring of experienced intern Shifting personnel
Process	Quality testing of COTS component Install new machine	Switch production process Deploy product during different operations
Product	COTS component availability Modular design feature	Access new technology Use COTS component Reuse module in later designs
Service	On-orbit servicing system	Access to secure services online Service different numbers, types of satellites
Knowledge	Patenting Cross training of employees	License patent Leverage R&D results
IT	Investment in web design Redundancy in IT system	Allocate resources to late projects Revert to redundant system upon failure

Fig. 7. Examples of mechanisms and types across the enterprise views.

enables the option to expand or abandon the investment. Expansion of the investment is a mechanism that enables further options to expand or abandon, and so forth.

VI. EXAMPLES OF REAL OPTIONS IN ENTERPRISE ARCHITECTURE

Examples of mechanisms and types of options across the enterprise views are shown in Fig. 7. Each row in the figure corresponds to an enterprise view. The arrows indicate the relations among the mechanisms and types across the views. Within each of the enterprise views, the traditional types of options can be applied, such as the option to expand, contract and delay. Examples of multiple mechanisms that enable a single type of option and a mechanism that enables multiple types of options are also shown.

In the strategy view, an example of a mechanism is investment in university research, which enables an option to leverage the R&D results. Policy on IT security and an investment in web design are both required mechanisms to enable the online banking option in the service view. An example of a policy mechanism that enables a type of option in the process view is the “20% time” policy at Google, Inc. This policy gives flexibility to employees to spend 20% of their time working on projects that are not necessarily in their job description. The type of option is therefore in the process view, where employees have the option to choose their activities. An organizational partnership mechanism enables an option to expand collaboration to future projects. In the product and process views, the availability of a commercial off-the-shelf (COTS) component and testing its quality for a specific application are necessary to enable the option to use it. In the product view, a modular design feature such as a removable camera lens, enables multiple types of options across multiple enterprise views. These options include the strategy to charge customers for module upgrades (e.g., for upgrading to more sophisticated lens systems); using the product in multiple scenarios (e.g., for imaging at multiple zoom levels); and for reusing the module in different products (e.g., future cameras that are backwards compatible with existing lenses). In the service view, the deployment of an on-orbit satellite servicing system is a mechanism that enables the option

TABLE II
MECHANISM PATTERNS AND INSTANTIATIONS

Mechanism Patterns	Instantiation Examples
Modularity	modular architecture (product) task clustering (process)
Redundancy	multi sourcing (strategy) spares (product)
Buffering	cross-training (knowledge) reserve funds (strategy)
Staging	R&D investment (strategy) staged deployment of satellites (process)

for on-orbit servicing, while the capacity and types of satellites that may be served are examples of types of options. In the knowledge view, patenting is a mechanism that enables options to license the patent or to develop proprietary products based on the patent. Cross training of employees through departmental rotations is a knowledge acquisition mechanism that enables the option to shift personnel within the organization and assign them to a variety of tasks. Lastly, an example of a mechanism in the IT view is the investment in redundancy that enables the option to revert to backup systems upon failure.

VII. PATTERNS OF MECHANISMS

The \langle Mechanism, Type \rangle characterization suggests that patterns of mechanisms that enable real options can be identified and catalogued, in analogy with the documented types of real options [3]. Documenting patterns of mechanisms will allow their systematic application in new contexts and scenarios, similar to methods such as TRIZ [33] and design patterns [34]. A mechanism pattern may be specific to a single view or applicable to multiple enterprise views. Table II lists selected patterns of mechanisms along with some instantiations in enterprise views.

Modularity, or the creation of a common interface, is an example of mechanism pattern. In Design Rules [35], modularity is shown to create options such as splitting, substituting and augmenting. As a mechanism pattern, modularity can be applied to multiple enterprise views. In the process view, partitioning of tasks into independent clusters enables the option to execute tasks in parallel. A modular organization enables the option to split. For example, the division of function in microprocessor design and fabrication enabled Advanced Micro Devices, Inc. (AMD) to spin off its manufacturing, creating GlobalFoundries in a joint venture with the Advanced Technology Investment Company, in order to stay competitive.

Redundancy is a mechanism pattern that enables the option to revert to the redundant solution upon encountering failure scenarios. For example, Nokia has adopted a multi-sourcing mechanism involving an agreement with STMicroelectronics to supply 3G chipsets based on Nokia's modem technology, along with three other primary chipset suppliers: Texas Instruments, Broadcom and Infineon.

Buffering or the allocation of reserves is a mechanism pattern commonly used in the manufacturing domain. This pattern is reflected in the variability buffering law [36], which states that "variability in a production system will be buffered by some combination of inventory, capacity, and time." An example of

a time buffer mechanism in the process view is lengthening the lead time to deliver a product, which enables the option to delay the delivery. Cross-training is also a buffering mechanism [37] in the knowledge view because it enables the option to shift the employees to different tasks to manage uncertainty in task demands.

Staging is often identified in the real options literature as a type of real option. In light of the \langle Mechanism, Type \rangle characterization, we identify staging is a mechanism pattern that can be instantiated within multiple enterprise views. In the strategy view, staging an R&D investment enables the option to expand or abandon. In the knowledge view, patenting is a staging mechanism that enables the option to build a proprietary product or license the technology.

VIII. APPLICATION

The mapping of real options to enterprise architecture is a conceptual framework that enables holistic thinking about mechanisms and types of real options for uncertainty management. In this section, we leverage this mapping within the IRF and demonstrate its benefit over the localized approach through application to a surveillance mission.

A. Integrated Real Options Framework

We introduce the IRF for managing uncertainties through the identification and valuation of real options in enterprise architecture.

The IRF is shown in Fig. 8. It is based on the holistic enterprise architecture framework along with the concept of mapping the mechanisms and types of real options to the enterprise views. It also leverages patterns of mechanisms and types of real options. These are shown as inputs to the left of Fig. 8. We assume that uncertainties have been identified and input to the IRF. The application of IRF consists of two major steps: the identification of real options, followed by their valuation. The identification of real options to manage a given uncertainty may involve: 1) the identification of existing real options by analyzing the current enterprise architecture, and/or 2) the generation of new real options by synthesizing alternative \langle Mechanism, Type \rangle candidates that encompass the enterprise architecture views. Real options valuation methods are then applied to compare the identified \langle Mechanism, Type \rangle candidates. Based on the results of the valuation, recommendations can be made on whether the identified real options are worthwhile under uncertainty. If a decision is made to implement (or eliminate) a real option, the enterprise architecture will be changed accordingly by adding (or removing) corresponding types and mechanisms.

Within the IRF, specific methods for identifying the mechanisms and types of real options can be devised. The chosen method will depend on the intended application of the IRF. One potential application is a bottom-up analysis of an enterprise architecture to identify and document existing real options for managing a myriad of uncertainties (for example, see Fig. 7 in Section VI). This application involves the analysis of existing real options. In this case, a model-based approach to identifying the real options will be most helpful for complex

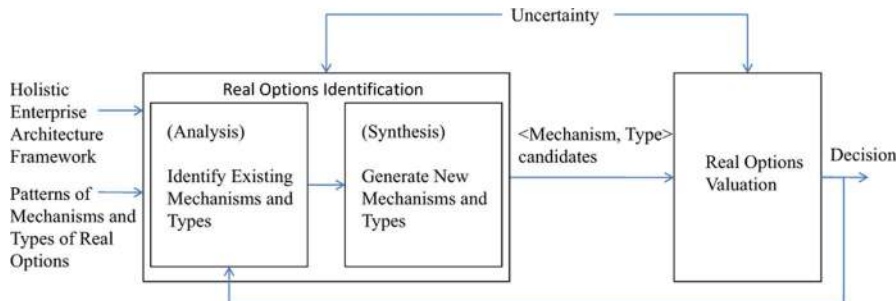


Fig. 8. Integrated real options framework.

enterprise architectures. Whereas the detailed treatment of model-based approaches is beyond the scope of this paper, we provide insight on how they can be used in the context of IRF. While the eight views of enterprise architecture constitute a conceptual framework for organizing the information relevant to the enterprise, it is possible to apply specific models for representing the enterprise architecture. For example, one can model the enterprise architecture using a logical coupled dependency structure matrix (logical C-DSM) [38]. The logical C-DSM is an expressive variant of the dependency structure matrix (DSM) [39] that has been used extensively for modeling and analysis of interdependencies in complex engineering projects [40]–[42]. The logical C-DSM has the expressivity to 1) model multiple domains and 2) model logical relations among dependencies. The first capability is important for modeling the multiple views of the enterprise architecture framework, whereas the second capability is important for modeling logical relations among mechanisms and types of real options, as discussed in Section V. Therefore, such a representation may form the basis for model-based identification of mechanisms and types [38], [43].

The application that we focus on is a top-down approach driven by a specific decision or a new scenario that benefits from the holistic perspective in identifying real options for uncertainty management. This application involves the generation of new combinations of mechanisms and types of real options, if existing options are not tailored to managing a given uncertainty. From this planning perspective, the holistic enterprise architecture framework provides a conceptual rather than a model-based approach to systematically synthesize new options within and across the enterprise views. In the following section, we demonstrate this application of the IRF in the context of a surveillance mission, with an emphasis on the benefit derived from the holistic identification of mechanisms and types of real options in the enterprise architecture.

B. Example: Surveillance Mission

As an example, consider an uncertainty in the required rate of acquiring imagery for surveillance missions, in the context of an enterprise responsible for supplying intelligence, surveillance, and reconnaissance (ISR) data. In this example, we assume that the current enterprise architecture does not embed real options for managing this uncertainty, thereby necessitating the synthesis of new combinations of mechanisms and types of real options.

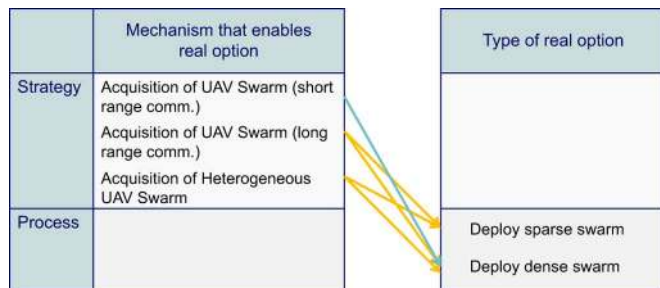


Fig. 9. Localized synthesis of mechanisms and types of real options.

1) *Localized Synthesis*: An *ad hoc* approach will most likely result in the identification of real options candidates within a specific silo, as reflected by the multitude of isolated real options applications in the literature (recall discussion in Section III-C). Fig. 9 shows a mapping of some candidate mechanisms and types of real options to the enterprise views. In this case, only the strategy and process views are considered. It is shown that the uncertainty in the rate of acquiring imagery can be managed through real options to deploy sparse and dense swarms of UAVs under the constraint of maintaining UAV-to-UAV connectivity among neighbors. While the case of swarms with long-range communication and the heterogeneous swarm with both short-range and long-range communication are mechanisms that enable both deploying dense and sparse swarms, a UAV swarm with short-range communication only enables deploying a dense swarm given the communication constraint.

2) *Holistic Synthesis Using IRF*: Next, we apply the IRF to demonstrate the benefit of the holistic approach to identifying real options in the enterprise architecture. This is accomplished by considering combinations of mechanisms and types of real options within and across all the enterprise views: strategy, policy, organization, process, product, service, knowledge, and IT. Fig. 10 shows alternative types of options to manage the uncertainty and associated mechanisms mapped to the enterprise views. The instantiation of patterns of mechanisms and types of real options within each of the views supports the synthesis of new real options. For example, the option to request a high rate of satellite imagery is derived from the instantiation of the real option to expand in the service view. Similarly, training of additional pilots is derived from the instantiation of the buffering mechanism pattern in the process view.

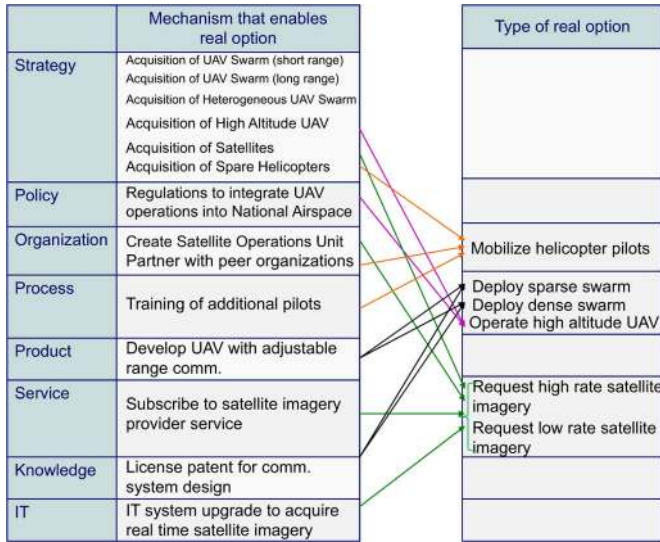


Fig. 10. Using IRF for holistic synthesis of mechanisms and types of real options in the enterprise architecture.

As shown in Fig. 10, the uncertainty in the requested rate of imaging can alternatively be managed through flexibility in the service view, and more specifically through options to request satellite imagery at flexible rates. In the organization view, the uncertainty can be managed through an option to mobilize helicopter pilots. In the process view, an alternative type of option is to operate a high-altitude UAV.

Alternative mechanisms for enabling the new types of options have also been identified by considering all the enterprise views. For example, the options to request satellite imagery (service view) at flexible rates can be enabled by: 1) subscribing to a satellite imagery provider service (service view) and investing in an IT system upgrade to accommodate receiving real time imagery (IT view), or alternatively, 2) acquisition of a satellite (strategy view), creation of a satellite operations division (organization view) and an investment in IT (IT view). The option to mobilize helicopter pilots (organization view) can be enabled through: 1) partnership with peer organizations that can provide additional helicopters and pilots (organization view), or 2) acquisition of spare helicopters (strategy view) and training of additional pilots (process view). The option to operate a high-altitude UAV (process view) can be enabled by the introduction of regulations to integrate UAV operations into national airspace (policy view) and the acquisition of a high-altitude UAV (strategy view). Lastly, an alternative mechanism that enables the options to deploy both sparse and dense swarms is to license a patent for the design of an adjustable range communication system (knowledge view) and to develop a UAV that implements this technology (product view). Note that the examples described above exhibit the various relations among the mechanisms and types of real options that were discussed in Section V.

In order to prescribe which of the identified real options in the enterprise architecture are worthwhile investments under uncertainty, we value the alternatives by modeling uncertainty, costs and benefits. We demonstrate the benefit of considering

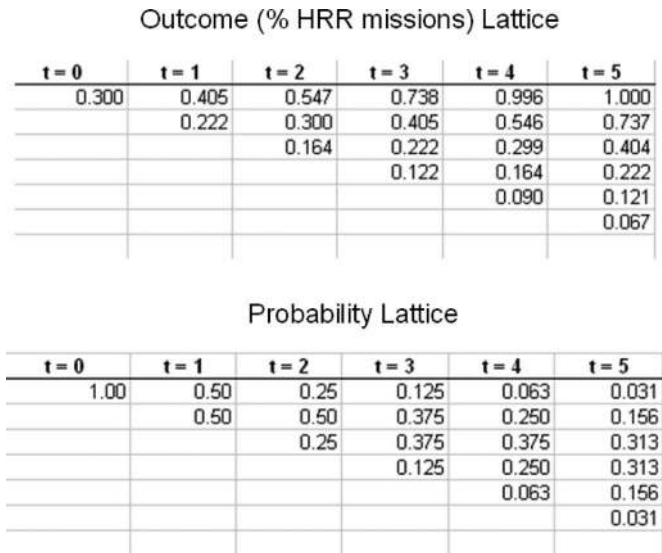


Fig. 11. Model of uncertainty.

the holistic enterprise architecture by showing how an alternative identified using the IRF (see Fig. 10) is more valuable than the baseline combinations in Fig. 9. In particular, we focus on valuation of the following <Mechanism, Type> tuples: 1) <{Acquisition of Short-range UAV Swarm}, {Deploy Sparse Swarm}>; 2) <{Acquisition of long-range UAV Swarm}, {Deploy Sparse Swarm, Deploy Dense Swarm}>; 3) <{Acquisition of Heterogeneous UAV Swarm}, {Deploy Sparse Swarm, Deploy Dense Swarm}>; 4) <{License Patent for Adjustable Range Communication System, Develop Adjustable Range UAV Swarm}, {Deploy Sparse Swarm, Deploy Dense Swarm}>.

3) *Uncertainty Model*: Since the uncertainty is whether future surveillance missions will need to provide imagery of targets at a low refresh rate (LRR) or high refresh rate (HRR), the uncertain outcome is modeled as the percentage of HRR missions. We develop a binomial lattice model [4], [27] (see Section III) to represent the evolution of the uncertain outcome in time (see Fig. 11).

The outcome lattice models the percentage of high refresh rate missions from time $t = 0$ to $t = 5$. The probability lattice represents the probability of each entry in the outcome lattice.¹ The models are generated based on the lattice parameters u , d , and p , which are calculated using the following equations [4]:

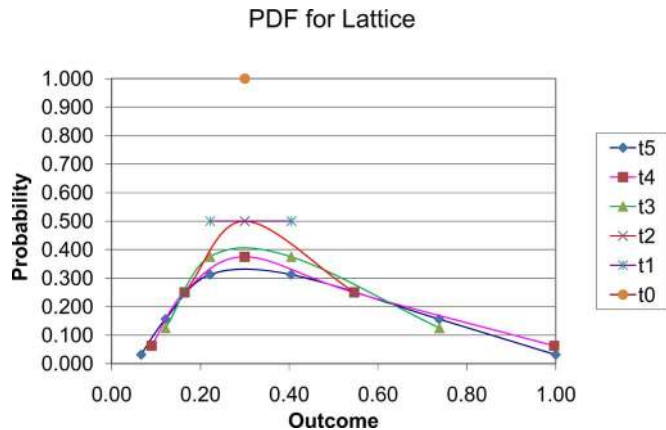
$$u = e^{\sigma \cdot \sqrt{dt}} = e^{0.3} = 1.35 \tag{1}$$

$$d = e^{-\sigma \cdot \sqrt{dt}} = 1/u = 0.74 \tag{2}$$

$$p = 0.5 + 0.5 \cdot (v/\sigma) \cdot \sqrt{dt} = 0.5 \tag{3}$$

where u is an upside multiple by which each node value in the lattice increases in the subsequent step; d is a downside multiple by which each node value in the lattice decreases in the subsequent step; p is the probability of transitioning to an upside

¹Note that since the outcome is a percentage and cannot exceed 100% in the lattice model, it is set to 1 (i.e., 100%) if it exceeds 100%.

Fig. 12. PDF of uncertainty for times t_0, \dots, t_5 .

value from a given node, dt is the time period increment, v is the growth rate of the HRR missions, and volatility is modeled by standard deviation σ . In this example, we assumed that the starting percentage S of HRR missions is 30%, $v = 0\%$, and $\sigma = 30\%$. Based on the outcome and probability lattices, Fig. 12 plots the probability distribution for the percentage of HRR missions from time $t = 0$ to $t = 5$.

4) *Quantification of Relative Benefits and Costs*: In order to proceed with real options valuation, the costs, benefits, and value of each swarm configuration under different scenarios are modeled. The benefits of the surveillance mission are derived from the images taken by the swarm. The number of images taken by each swarm configuration under the different scenarios is used as a metric to quantify benefits. The number of images is proportional to the number of UAVs in the swarm, the threshold number of images beyond which benefit is not derived, the refresh rate of targets and the duration of the mission. We consider alternative swarms consisting of four UAVs with identical sensor footprints, and assume that the UAVs fly equidistantly in a circular trajectory over targets with identical image refresh rates. The relative benefits (and costs) of the swarm configurations are important for comparative valuation of real options. A normalized benefits model based on the number of imagery is shown for each of the swarm configurations and deployment scenarios in Fig. 13.

- 1) Four UAVs with short-range communication system (SR): may only be deployed in a dense swarm configuration, in both the LRR and HRR missions. Assuming that for an HRR mission, two images are taken every minute, and the duration of the entire mission is 200 min, 400 images will be taken. For the LRR mission, one image is taken every minute, resulting in 200 images per mission. In case of the LRR mission, deploying a dense swarm is not ideal, because it exceeds the required one image per minute threshold refresh rate of the targets. The extra UAVs are deployed for maintaining network connectivity. The benefits are normalized around the 200 images per mission, as shown in Fig. 13.
- 2) Four UAVs with long-range communication system (LR): provide the option of being deployed in either sparse or dense swarms. In case of a HRR mission, all the UAVs are

Swarm	Normalized Benefits for LRR and HRR Missions			
	LRR	Benefit	HRR	Benefit
Short Range (SR)		1.00		2.00
Long Range (LR)		1.75		1.75
Heterogeneous Swarm (HS)		1.38		1.88
Adjustable Range (AR)		1.88		2.00

Fig. 13. Normalized benefits model.

TABLE III
RELATIVE COSTS AND VALUES NORMALIZED AROUND 200 IMAGES

Swarm	Cost/Mission	Value/LRR	Value/HRR
SR	0.22	0.78	1.78
LR	0.24	1.51	1.51
HS	0.23	1.15	1.65
AR	0.19	1.69	1.81

deployed. Note that the benefit is modeled as 350 images in this case (normalized as 1.75) because the long-range communication system consumes more power, resulting in a shorter period of operation. In case of a LRR mission, only two UAVs are deployed. The relative benefit in this case is modeled as 1.75 to account for both the reduced duration of operation and the opportunity to run a simultaneous mission with the extra UAVs.

- 3) Heterogeneous swarm of equal mix of UAVs with short and long-range communication systems (HS): may be deployed in both LRR and HRR missions. In both cases, the benefit is the average of the SR and LR scenarios.
- 4) Four UAVs with adjustable range communication system (AR): may be deployed in HRR and LRR missions. In the HRR case, all the UAVs will be deployed in the short-range mode, resulting in performance identical to the SR swarm. In the LRR case, two UAVs will be deployed in long-range mode with reduced operational duration due to increased power consumption. However, the benefit is modeled as 1.88 to capture the benefit derived from the simultaneous operation of the other two UAVs that do not have range restrictions.

The relative costs and values per mission are shown in Table III. The costs are normalized on the same scale as the benefits in Fig. 13, around 200 images per mission. For the acquisition of the SR, LR, and HS swarms, the cost per mission is the amortized cost of the UAVs, taking into account that the LR communication system is more costly than the SR system. For the AR swarm, cost is associated with two mechanisms: licensing of the technology and upgrade of in-house UAVs to use this technology, including the cost of the in-house UAVs. The

SR:	0	1	2	3	4	5
	5.11	4.91	4.60	4.10	3.25	1.78
		4.12	3.74	3.23	2.53	1.52
			3.25	2.72	2.06	1.18
				2.44	1.79	1.00
					1.65	0.90
						0.85
LR:	0	1	2	3	4	5
	6.95	6.10	5.14	4.06	2.86	1.51
		6.10	5.14	4.06	2.86	1.51
			5.14	4.06	2.86	1.51
				4.06	2.86	1.51
					2.86	1.51
						1.51
HS:	0	1	2	3	4	5
	6.05	5.52	4.89	4.09	3.06	1.65
		5.13	4.45	3.66	2.70	1.52
			4.21	3.40	2.47	1.35
				3.26	2.34	1.26
					2.26	1.21
						1.18
AR:	0	1	2	3	4	5
	7.96	7.03	5.98	4.79	3.41	1.81
		6.94	5.88	4.68	3.33	1.78
			5.82	4.62	3.27	1.74
				4.59	3.24	1.72
					3.22	1.70
						1.70

Fig. 14. Binomial lattice valuation.

normalized values per LRR and HRR mission are calculated as benefit minus cost.

5) *Comparison of Alternatives*: Using the uncertainty model presented above, the expected net present value (ENPV) of each of the <Mechanism, Type> candidates identified is calculated using the binomial lattice valuation (see Section III). The results are shown in Fig. 14.

The ENPV values are interpreted relative to each other. The ENPV of the UAVs with short-range communications is found to be 5.11 per mission. Acquisition of the swarm with long-range communication and the heterogeneous swarm are both mechanisms that result in the options to deploy sparse and dense swarms. These alternatives are valued at 6.95 and 6.05, respectively. The most valuable <Mechanism, Type> candidate in this example is <{License Patent for Adjustable Range Communication System, Develop Adjustable Range UAV Swarm}, {Deploy Sparse Swarm, Deploy Dense Swarm}>, valued at 7.96. Compared to the least valuable alternative, the added value of this real option is $7.96 - 5.11 = 2.85$. This example demonstrates that a holistic identification of mechanisms and types of real options across all the enterprise views may generate more valuable alternatives compared to an approach which is localized to specific views. The baseline alternatives (SR, LR, HS) involved mechanisms localized to the strategic acquisition of UAVs. On the other hand, the most valuable real option in this case consisted of multiple mechanisms encompassing both the knowledge and product views, which enabled multiple types of real options (to expand/contract the UAV swarm) in the process view.

IX. COMPARISON TO RELATED WORK

Through application of the IRF to a surveillance scenario in the previous section, we have demonstrated that an alternative

real option developed through the holistic approach is better than those that would have been generated through a localized approach. In this section, we compare the IRF to related work in the literature.

Prior work on ROA has focused on the quantitative valuation of real options, without much attention to how the alternatives that are being valued have been identified or enumerated. Furthermore, the alternatives that are valued are often localized to specific domains, such as IT investments [44], R&D investments and processes [45], [46], and product design [8], [47]. The IRF is distinguished from these valuation-centric approaches because it explicitly incorporates both the identification and valuation of real options. The focus on identification is motivated by a growing interest in new methods to identify and embed real options in enterprises in order to enable a more proactive management of uncertainty. However, most of the emerging methods for identifying real options are domain specific. For example, a change propagation index approach is used in [48] to identify where to insert flexibility in product design in order to suppress change propagation. Another approach described in [16] is to identify hot spots in a system that are expected to change frequently as candidate locations to embed real options. These approaches differ from the IRF in that they are most appropriate for change management versus uncertainty management, and are restricted to the identification of mechanisms in a product centric view. Other approaches focus solely on the identification of types of real options rather than mechanisms. For example, risk-option relationships for IT projects are identified in [49], [50]. That approach is complementary to the IRF because it addresses the mapping of types of real options to categories of uncertainties, whereas our approach focuses on mapping of mechanisms to types of real options for managing given uncertainties. Also, the IRF considers a more holistic enterprise architecture rather than being unique to the IT view. In summary, the IRF has two key advantages in comparison to emerging approaches to real options identification. The first is the identification of both mechanisms and types of real options for managing uncertainties. The second is consideration of a holistic enterprise architecture rather than a specific view such as product or IT.

Another relevant dimension for comparison is the holistic enterprise architecture framework used within the IRF. Comparison to IT-centric enterprise architecture frameworks was discussed in Section II. In Section VIII-A, we also discussed the possibility of using specific representation models such as dependency structure matrices [43] within the enterprise architecture framework, although treatment of modeling formalisms is beyond the scope of this paper. Future work can consider the use of modeling languages including those originally devised for specification of software and IT systems. For example, the Universal Systems Language (USL) [51] is a formal modeling language with an underlying semantics that can support SysML [52]. USL and SysML can potentially be adapted for the formal specification of the holistic enterprise architecture along with the logical relations among mechanisms and types.

Next, we compare the IRF to some prominent methods for decision making under uncertainty: scenario planning, decision trees, and simulations. Scenario planning [53] is a qualitative

approach to the identification of trends, uncertainties, and possible futures. The goal of scenario analysis is to broaden the scope of future scenarios considered through structured thinking, thereby enabling the consideration of otherwise unanticipated events. In contrast, the IRF provides a qualitative framework to broaden the scope of real options identification for managing given uncertainties. These two approaches are therefore compatible and may be combined to incorporate broader consideration of both uncertainties and real options. An approach that combines scenario planning with real options is proposed in [54], where various types of real options are mapped to uncertainties identified using scenario planning. However, that approach does not address how the alternative real options are identified, and instead focuses on leveraging the mapping of real options to uncertainties for qualitative assessment of risk.

Decision tree analysis involves constructing a tree where the layers of nodes alternatively represent decision and chance outcomes, and the leaves represent the final outcomes of paths in the tree. Uncertainties are modeled with probabilities of chance nodes. Decision analysis calculates the best decision path to take by maximizing the expected value of the outcomes. Decision trees and their variants have been used for real options valuation [45], [55], as an alternative to financial valuation models (see Section III). For example, binomial decision trees have been devised in [55] as a more intuitive alternative to the binomial lattice valuation method. However, decision trees suffer from an exponential growth with the number of variables modeled.

Simulations have also been widely used to support decision making uncertainty. However, simply simulating the variability of future outcomes to decide among alternatives may not be sufficient. For example, it has been shown in [56] that simulation of uncertainty will result in a suboptimal solution if the flexibility to also respond to the uncertainties is not simulated. Therefore, simulation alone is not a replacement of the real options approach, but can be used to value the real options as described in Section III. The modularity of the IRF enables the selection of a real options valuation method that is suited to a specific application.

Note that this paper dealt with the real options approach to uncertainty management. An empirical comparison to other uncertainty management approaches, such as diversification, is beyond the scope of this paper and is recommended for future work. While we showed that the IRF is better than traditional localized ROA, it also inherits limitations of real options approaches. For example, real options are most appropriate for managing uncertainties that are anticipated to be resolved in the future, and are not well suited for managing unknown unknowns. Therefore, the use of IRF should consider the application context, and may be complemented by alternative approaches to uncertainty management.

Real options methods have been criticized for being strictly quantitative. However, qualitative approaches are emerging, both for valuation [53], [57] and identification of real options [48], [49]. Research into the state of real options practice has revealed that qualitative real options thinking is often cited as the key benefit of real options and that “a shorthand language to characterize strategic elements of a project does seem to be

valuable” [58]. The <Mechanism, Type> characterization of a real option and its mapping to a holistic enterprise architecture framework enables a more structured and holistic qualitative approach to real options identification.

X. CONCLUSION

In this paper, we developed the qualitative foundation for holistic consideration of real options in enterprise architecture. We characterized real options through enabling mechanisms and resulting types of options. We then established the link between the new real options model and enterprise architecture through a mapping of mechanisms and types of options to the enterprise architecture. In particular, we used a multiview framework to support a holistic identification of real options beyond the boundaries of enterprise silos. We leveraged these developments in an IRF and demonstrated its benefit over traditional ROA in identifying a broader spectrum of real options for uncertainty management.

In the discussion of challenges in Section I, we posed the following motivating questions: 1) what type of flexibility is desirable to manage uncertainty? 2) how to enable such flexibility?, and 3) where to implement flexibility in an enterprise? These challenges can be addressed respectively through: 1) identification of existing and new *types* of real options that can manage the uncertainty and that can be located within any of the enterprise views, 2) identification of existing and new *mechanisms* that enable these types of real options and that can be located within any of the enterprise views, and 3) valuation of the identified alternative mechanisms and types of real options that encompass the enterprise views.

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REFERENCES

- [1] J. L. Hall, “Columbia and challenger: organizational failure at NASA,” *Space Policy*, vol. 19, pp. 239–247, 2003.
- [2] S. C. Myers, “Finance theory and financial strategy,” *Interfaces*, vol. 14, no. 1, pp. 126–137, 1984.
- [3] L. Trigeorgis, *Real Options: Managerial Flexibility and Strategy in Resource Allocation*. Cambridge, MA: MIT Press, 1998.
- [4] T. Copeland and V. Antikarov, *Real Options: A Practitioner's Guide*. London, U.K.: Texere, 2001.
- [5] A. Dixit and R. Pindyck, *Investment under Uncertainty*. Princeton, NJ: Princeton Univ. Press, 1994.
- [6] R. de Neufville, “Real options: Dealing with uncertainty in systems planning and design,” *Integr. Assessment*, vol. 4, no. 1, pp. 26–34, 2003.
- [7] O. de Weck, R. de Neufville, and M. Chaize, “Staged deployment of communication satellite constellation in low earth orbit,” *J. Aerosp. Comput. Inf. Commun.*, vol. 1, no. 3, pp. 119–131, 2004.
- [8] R. Hassan, R. de Neufville, and D. McKinnon, “Value-at-risk analysis for real options in complex engineered systems,” in *Proc. IEEE Int. Conf. Syst., Man, Cybern.*, Waikoloa, Hawaii, Oct. 2005.
- [9] E. M. Murman, T. Allen, K. Bozdogan, J. Cutcher-Gershenfeld, H. McManus, D. Nightingale, E. Reberntsch, T. Shields, F. Stahl, M. Walton, J. Warmkessel, S. Weiss, and S. Widnall, *Lean Enterprise Value: Insights from MIT's Lean Aerospace Initiative*. New York, NY: Palgrave, 2002.
- [10] J. Schekkerman, *How to Survive in the Jungle of Enterprise Architecture Frameworks*. Bloomington, IN: Trafford Publishing, 2004.

- [11] J. Schekkerman. (2005). Trends in enterprise architecture, Inst. Enterprise Architecture Dev., Tech. Rep. [Online] Available: <http://enterprise-architecture.info/>
- [12] J. Zachman. (2009 Sep.). The Zachman Institute for Framework Architecture [Online]. Available: <http://www.zifa.com/>
- [13] T. O. Group. (2009 Sep.). The open group architecture framework (TOGAF 9) [Online]. Available: <http://www.opengroup.org/togaf/>
- [14] (2009 Sep.). DoD architecture framework [Online]. Available: <http://www.defenselink.mil/cio-nii/>
- [15] T. C. I. O. Council. (2009 Sep.). Federal enterprise architecture framework (FEAF) [Online]. Available: <http://www.cio.gov/library/library.cfm>
- [16] J. E. Bartolomei, "Qualitative knowledge construction for engineering systems: extending the design structure matrix methodology in scope and procedure," Ph.D. dissertation, MIT, Cambridge, MA, 2007.
- [17] J. W. Ross, P. Weill, and D. Robertson, *Enterprise Architecture As Strategy: Creating a Foundation for Business Execution*. Boston, MA: Harvard Business School Press, 2006.
- [18] E. Reichtin, *Systems Architecting of Organizations: Why Eagles Can't Swim*. Boca Raton, FL: CRC Press, 1999.
- [19] D. J. Nightingale and D. H. Rhodes, "Enterprise systems architecting: emerging art and science within engineering systems," in *MIT Engineering Systems Symposium*, Mar. 2004.
- [20] D. J. Nightingale and D. H. Rhodes, 2007, MIT Enterprise Architecting Class Notes.
- [21] D. H. Rhodes, A. M. Ross, and D. J. Nightingale, "Architecting the system of systems enterprise: enabling constructs and methods from the field of engineering systems," presented at 3rd Annual IEEE Int. Syst. Conf., Mar. 2009, Vancouver, BC, Canada.
- [22] D. J. Nightingale, "Principles of enterprise systems," presented at the 2nd Int. Symp. Eng. Syst., 2009, Cambridge, MA.
- [23] M. Hammer and S. Stanton, "How process enterprises really work," *Harvard Bus. Rev.*, vol. 77, no. 6, pp. 108–118, Nov. 1999.
- [24] W. Rouse, "Enterprises as systems: Essential challenges and enterprise transformation," *Syst. Eng.*, vol. 8, no. 2, pp. 138–150, 2005.
- [25] F. Black and M. Scholes, "The pricing of options and corporate liabilities," *J. Political Econ.*, vol. 81, pp. 637–654, 1973.
- [26] R. C. Merton, "The theory of rational option pricing," *Bell J. Math. Manage. Sci.*, vol. 4, no. 1, pp. 141–183, 1973.
- [27] J. C. Cox, S. A. Ross, and M. Rubinstein, "Option pricing: a simplified approach," *J. Financial Econ.*, vol. 7, pp. 229–263, 1979.
- [28] P. P. Boyle, "Options: a Monte Carlo approach," *J. Financial Econ.*, vol. 4, pp. 323–338, 1977.
- [29] W. Rouse, C. Howard, W. Carns, and E. J. Prendergast, "Technology investment advisor: An options-based approach to technology strategy," *Inf.-Knowl.-Syst. Manage.*, vol. 2, pp. 63–81, 2000.
- [30] B. Miller and J.-P. Clarke, "Strategic guidance in the development of new aircraft programs: a practical real options approach," *IEEE Trans. Eng. Manag.*, vol. 55, no. 4, pp. 566–578, Nov. 2008.
- [31] T. Wang and R. de Neufville, "Identification of real options "in" projects," in *Proc. 16th Int. Symp. Int. Council Syst. Eng.*, Orlando, FL, Jul. 2006.
- [32] J. McConnell, "A life-cycle flexibility framework for designing, evaluating and managing "complex" real options: Case studies in urban transportation and aircraft systems," Ph.D. dissertation, MIT, Cambridge, MA, 2007.
- [33] M. A. Orloff, *Inventive Thinking Through TRIZ: A Practical Introduction*. Berlin, Germany: Springer, 2003.
- [34] E. Gamma, R. Helm, R. Johnson, and J. M. Vlissides, *Design Patterns: Elements of Reusable Object-Oriented Software*. Reading, MA: Addison-Wesley, 1994.
- [35] C. Y. Baldwin and K. B. Clark, *Design Rules: The Power of Modularity*. Cambridge, MA: MIT Press, 2000.
- [36] W. Hopp and M. Spearman, *Factory Physics*. Boston, MA: Irwin/McGraw-Hill, 2000.
- [37] S. C. Graves, *Building Intuition: Insights from Basic Operations Management Models and Principles*. New York: Springer Sci. Bus. Media, LLC, 2008, ch. 3, pp. 33–49.
- [38] T. Mikaelian, "An integrated real options framework for model-based identification and valuation of options under uncertainty," Ph.D. dissertation, MIT, Cambridge, MA, 2009.
- [39] D. V. Steward, "The design structure system: a method for managing the design of complex systems," *IEEE Trans. Eng. Manag.*, vol. 28, no. 3, pp. 71–74, Aug. 1981.
- [40] T. R. Browning, "Applying the design structure matrix to system decomposition and integration problems: A review and new directions," *IEEE Trans. Eng. Manag.*, vol. 48, no. 3, pp. 292–306, Aug. 2001.
- [41] S. Cho and S. Eppinger, "A simulation-based process model for managing complex design projects," *IEEE Trans. Eng. Manag.*, vol. 52, no. 3, pp. 316–328, Aug. 2005.
- [42] D. Batallas and A. Yassine, "Information leaders in product development organizational networks: social network analysis of the design structure matrix," *IEEE Trans. Eng. Manag.*, vol. 53, no. 4, pp. 570–582, Nov. 2006.
- [43] T. Mikaelian, D. H. Rhodes, D. J. Nightingale, and D. E. Hastings, "Model-based estimation of flexibility and optionability in an integrated real options framework," presented at 3rd Annu. IEEE Int. Syst. Conf., Vancouver, BC, Canada, Mar. 2009.
- [44] L. Hui and Z. Qiuyan, "Research on enterprise information system implementation decision based on real options approach," in *Proc. IEEE Int. Conf. Syst., Man, Cybern.*, 2007, pp. 3887–3891.
- [45] L. P. Santiago and T. G. Bifano, "Management of R&D projects under uncertainty: A multidimensional approach to managerial flexibility," *IEEE Trans. Eng. Manag.*, vol. 52, no. 2, pp. 269–280, May 2005.
- [46] A. Huchzermeier and C. H. Loch, "Project management under risk: using the real options approach to evaluate flexibility in R&D," *Manag. Sci.*, vol. 47, no. 1, pp. 85–101, 2001.
- [47] J. Jiao, A. Kumar, and C. M. Lim, "Flexibility valuation of product family architecture: a real-option approach," *Int. J. Adv. Manuf. Technol.*, vol. 30, pp. 1–9, 2006.
- [48] O. de Weck and E. S. Suh, "Flexible product platforms: framework and case study," presented at ASME 2006 Int. Des. Eng. Tech. Conf. Comput. Inform. Eng. Conf., Philadelphia, PA, 2006.
- [49] M. Benaroch, Y. Lichtenstein, and K. Robinson, "Real options in IT risk management: An empirical validation of risk–option relationships," *MIS Q.*, vol. 30, no. 4, pp. 827–864, 2006.
- [50] M. Benaroch, "Managing information technology investment risk: A real options perspective," *J. Manag. Inf. Syst.*, vol. 19, pt. 2, pp. 43–84, 2002.
- [51] M. H. Hamilton and W. R. Hackler, "Universal systems language: lessons learned from Apollo," *IEEE Computer*, vol. 12, pp. 34–43, 2008.
- [52] M. H. Hamilton and W. R. Hackler, "A formal universal systems semantics for SysML," presented at 17th Int. Symp. Int. Council Syst. Eng., San Diego, CA, 2007.
- [53] G. Ringland, *Scenario Planning: Managing for the Future*. Hoboken, NJ: Wiley, 2006.
- [54] K. D. Miller and H. G. Waller, "Scenarios, real options, and integrated risk management," *Long Range Planning*, vol. 36, pp. 93–107, 2003.
- [55] L. E. Brandão, J. S. Dyer and W. J. Hahn, "Using binomial decision trees to solve real-option valuation problems," *Decis. Anal.*, vol. 2, no. 2, pp. 69–88, 2005.
- [56] R. de Neufville, S. Scholtes, and T. Wang, "Real options by spreadsheet: parking garage case example," *J. Infrastructure Syst.*, vol. 12, no. 2, pp. 107–111, 2006.
- [57] G. N. Angelou and A. A. Economides, "A decision analysis framework for prioritizing a portfolio of ICT infrastructure projects," *IEEE Trans. Eng. Manag.*, vol. 55, no. 3, pp. 479–495, Aug. 2008.
- [58] A. Triantis and A. Borison, "Real options: State of the practice," *J. Appl. Corporate Finance*, vol. 14, no. 2, pp. 8–24, 2001.



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