

The following paper was published and presented at the 3rd Annual IEEE Systems Conference in Vancouver, Canada, 23-26 March, 2009.

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Model-based Estimation of Flexibility and Optionability in an Integrated Real Options Framework

Tsoline Mikaelian*, Donna H. Rhodes, Deborah J. Nightingale and Daniel E. Hastings

Department of Aeronautics and Astronautics and Engineering Systems Division

Massachusetts Institute of Technology

Cambridge, MA, USA

*tsoline@mit.edu

Abstract—Uncertainties can be managed through real options that provide a decision maker the right, but not the obligation, to exercise actions at a later time. In previous work [1] we introduced an integrated real options framework (IRF) that distinguishes among option mechanism and type. The mechanism is the enabler of the option, while the type refers to the flexibility provided by the option. The idea behind IRF is to use models of a system or enterprise as a coupled dependency structure matrix (C-DSM) in order to identify and value enablers and types of flexibility. In this paper, we first show how the distinction among mechanisms and types of options leads to the identification of some new “ilities”, such as optionability, that are relevant to the options identification problem. Second, we show that the semantics of a traditional dependency model does not allow for the representation and estimation of flexibility and optionability. Therefore, we extend the C-DSM model to a logical C-DSM that is capable of representing logical relations among dependencies. Finally, we present metrics for estimating flexibility and optionability from the logical C-DSM model. We discuss the results of applying these metrics to identify mechanisms and options in purchasing a swarm of uninhabited air vehicles.

Keywords- *real option, flexibility, uncertainty, dependency model, metric, system, enterprise*

I. INTRODUCTION

Uncertainties can be managed through real options that provide a decision maker the right, but not the obligation, to exercise actions at a later time. This paper is based on the formulation of flexibility as a real option since this formulation enables the use of quantitative real options valuation techniques [2] to value flexibility in systems or enterprises. The real options formulation has been previously used to value flexibility in various applications, ranging from capital investment decisions to the valuation of flexibility in system design [3,4,5]. However, in an effort to actively manage uncertainties through flexibility, the valuation step must be preceded by the identification of where options are or can be embedded in a system or enterprise. This paper is motivated by the need to identify real options. Prior work on the identification of real options specifically focuses on identifying options in system design [5,7,8].

In previous work [1], we introduced an integrated real options framework (IRF) that distinguishes among a real option *mechanism* and *type* in order to enable a systematic exploration of real options opportunities. The mechanism enables a real

option or flexibility, while the type characterizes the exercisable action(s) of a real option. For example, design of an interchangeable payload bay for a mini air vehicle is a mechanism that enables an operational option to use the vehicle for a variety of missions. Given the distinction between the mechanism and type of an option, identification of options can be framed as two separate problems: first is the identification of the types of options, that is, the types of flexibility that can manage uncertainties; second is the identification of mechanisms that enable the options.

An important motivation for distinguishing among the option mechanism and type is that it enables a holistic identification of options. This is especially critical in systems or enterprises that have complex inter-dependencies, such that the cause and effect are not necessary co-located. An action taken in one part of the system may affect another part of the system. Similarly, a real option mechanism and resulting option are not necessarily co-located. A mechanism may result in an option in another part of the system or enterprise. For example, implementing a mechanism in product design may provide a real option in business strategy. In modeling a system or enterprise to identify options, it is important to capture the inter-dependencies that are most relevant to stakeholders while maintaining a holistic, end-to-end representation of system behavior [9]. This motivates the use of dependency network models such as the coupled dependency structure matrix (C-DSM) [1,4,9]. In the context of IRF, a system or enterprise is modelled as a C-DSM of dependencies among eight views: policies, strategies, organization, processes, products, services, knowledge and IT [1]. Mechanisms and types of real options may span any of these views.

In this paper, we first show how the distinction among mechanisms and types of options leads to some new “ilities”, such as optionability, that are relevant to the options identification problem. While flexibility characterizes the type of option and directly affects the value delivery in a system, optionability characterizes the option mechanism and is an enabler of flexibility. The rest of the paper focuses on metrics to estimate flexibility and optionability, i.e. to identify “where” these ilities are located, based on a C-DSM model. We show that the semantics of a traditional dependency model does not allow for the representation and estimation of these ilities. Therefore, we extend the C-DSM model to a logical C-DSM that incorporates the specification of logical structure among dependencies. We devise metrics for estimating flexibility and

The authors gratefully acknowledge funding for this research provided through MIT Systems Engineering Advancement Research Initiative (SEARI, <http://seari.mit.edu>), Singapore Defence Science and Technology Agency and DSO National Labs.

optionability based on the logical C-DSM model. We discuss the application of the metrics to identify real options for a swarm of uninhabited air vehicles.

II. FLEXIBILITY AND OPTIONABILITY

Uncertainty impacts value delivery, as shown in Fig. 1. However, a real option may be used to manage uncertainty. The type of option can directly impact value delivery under uncertainty, by acting as a dynamic switch. That is, depending on how the uncertainty is resolved in the future, the option may or may not be executed. For example, an extra battery on a micro air vehicle may be used only if the mission will require long flight duration. As shown in Fig. 1, the mechanism does not directly impact the value delivery; it rather it acts as an enabler to the type of option. In this example, the design of a flexible payload bay is the mechanism that enabled the option to accommodate an extra battery.

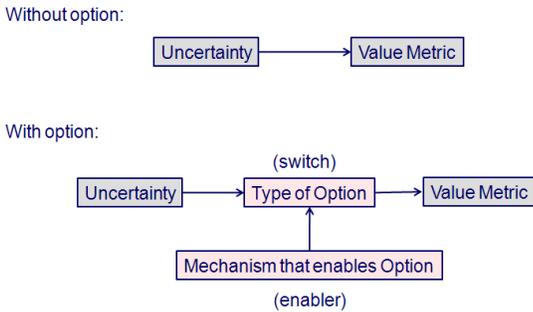


Figure 1. A real option type impacts value delivery under uncertainty, while a mechanism serves as an enabler to the type of option.

The type of real option reflects the ability to change in response to future events, and therefore can be characterized by flexibility. The conceptual distinctions among a mechanism and type of option lead to the identification of a new ility called optionability that is a property of an option mechanism. Since a mechanism is an enabler of a type of option, optionability may be considered an enabler of flexibility.

The distinction between the two ilities is depicted in Fig. 2. In a state transition model, flexibility is represented as the ability to switch to different nodes, while optionability is represented as the ability to switch to at least one node that is flexible.

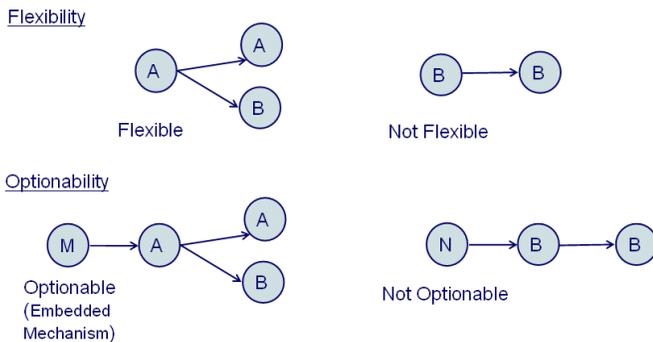


Figure 2. Flexibility versus Optionability.

III. MODEL-BASED ESTIMATION OF FLEXIBILITY AND OPTIONABILITY

In this section, we compare the semantics of a dependency model to that of a state machine model. The comparison is used to formulate metrics for estimating flexibility and optionability based on each of these models.

A. Semantics of the System Model

As a first step towards model-based estimation of the ilities, we compare the semantics of a C-DSM to that of a state machine, as shown in Fig. 3. A C-DSM is a dependency network where the nodes may represent various entities such as stakeholders, strategies, processes and products. The edges in a dependency model represent dependencies or influences among nodes. In Fig. 3, a dependency network is shown on the left. The dependency network is interpreted as node A affecting nodes B and C, and nodes B and C being affected by A.

In a state machine model, shown on the right of Fig. 3, the nodes represent states. A state is a typically a complete representation of a system or enterprise rather than a single entity within the system or enterprise. In the state machine model, the edges represent transitions among states. Therefore, the state machine in Fig. 3 is interpreted as state A having the potential to transition to state B or state C, state B having the potential to transition to states D, E, and F.

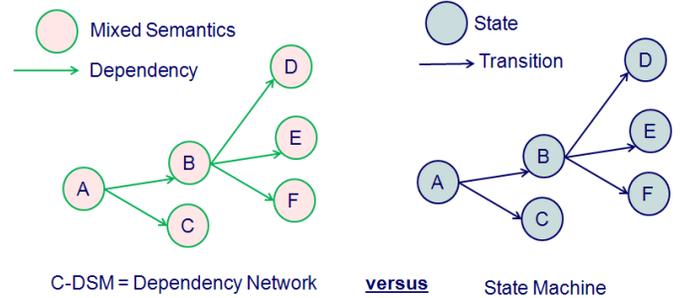


Figure 3. Dependency model (C-DSM) versus a state machine model.

Given the semantic differences between a dependency model and a state machine, we will first study flexibility and optionability metrics for a state machine, and then explore how analogous metrics may be developed for a C-DSM.

B. Flexibility and Optionability Metrics for a State Machine

Prior work has proposed metrics for estimating flexibility of system designs from state machine models [10]. The following are potential flexibility and optionability metrics for a state machine:

Flexibility indicator (Flex): Number of outgoing edges from a node.

Optionability indicator (Opt): Number of outgoing edges that lead to nodes with Flex > 1.

These metrics are consistent with the earlier example and abstraction (Fig. 2) presented to distinguish among flexibility and optionability.

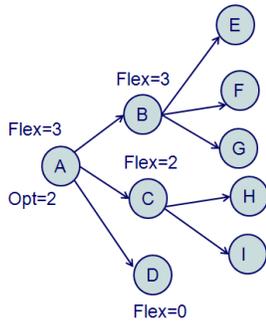


Figure 4. Metrics for flexibility and optionability.

Fig. 4 shows the calculation of these metrics for an example state machine. The following section discusses the flexibility metric in the context of a dependency model.

C. Flexibility Metric in State Machine versus C-DSM

The flexibility metric was defined in the previous section as the number of outgoing edges. This metric works in the case of a state machine because the transition model is a logical OR relationship, as shown in Fig. 5.

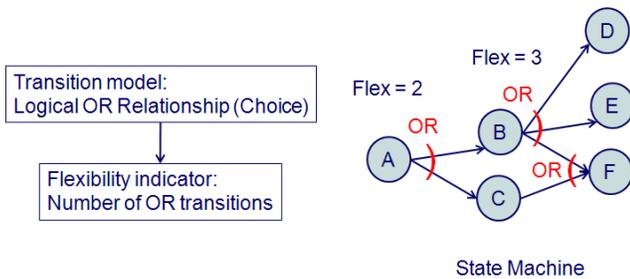


Figure 5. Transition model and flexibility indicator for a state machine.

The logical OR relationship is equivalent to having a choice among various transitions. For example state A may transition to either state B or state C. Therefore, Flex = 2 in this case for state A. Note that Flex \leq 1 indicates a nonflexible state.

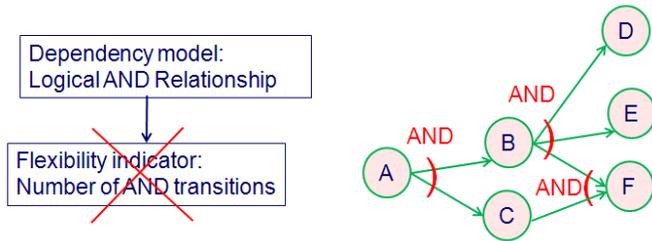


Figure 6. Transition model for a C-DSM; the flexibility indicator cannot be defined as the count of outgoing edges in this case.

However, this flexibility metric is not valid for a dependency model such as a C-DSM. The dependency model semantics is a logical AND relationship, as shown in Fig. 6. This is because node A affects both node B and node C. In the C-DSM model, node A will be modeled as affecting both nodes B and C. A conventional dependency model does not allow for

representation of the case where A may impact either B or C. Once there is a potential for node A to impact either B or C, both dependencies are modeled in the C-DSM. Therefore, a dependency model does not capture choice, and is not compatible with modeling flexibility by default. The following sections present an approach to addressing this limitation.

Example: As an example, consider the dependency model shown in Fig. 7. The actions “insert battery 1”, “insert battery 2” and “remove battery 2” all affect the endurance of a micro air vehicle. The dependency model is interpreted as having an “AND” semantics – that is, all three actions impact endurance. Therefore, the flexibility metric for the endurance node, which represents the flexibility of achieving the endurance objective, is less than the count of incoming edges in this case.

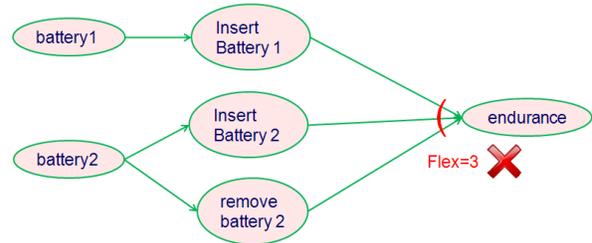


Figure 7. Example of dependency model

In order to correctly calculate the flexibility for achieving the endurance objective, it is necessary to identify and isolate the OR relationships in the model. This translates to identifying mutual exclusions in this example. As shown in Fig. 8, inserting both batteries 1 and 2 will provide enhanced endurance. Therefore, there is no flexibility in achieving enhanced endurance, as inserting both batteries is the only possible way to achieve enhanced endurance. Similarly, there is no flexibility in achieving normal endurance, because inserting battery 1 and removing battery 2 is the only way to achieve normal endurance. The overall endurance depends on both enhanced and normal modes. However, the endurance relationship is in fact an OR because endurance is either enhanced OR normal, not both. Therefore, the flexibility of achieving the endurance objective is may be estimated based on the number of choices in the OR relation and not by the AND relations.

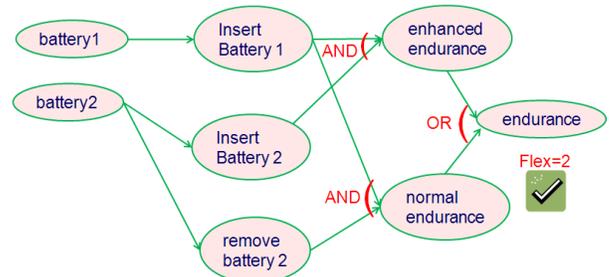


Figure 8. Isolating AND versus OR relationships in a dependency model.

In summary, the semantics of a dependency model, including a C-DSM, is the logical AND relationship. A dependency model does not distinguish among ANDs and ORs

in specifying dependencies. However, the evaluation of the flexibility metric must be based on the logical OR relationships, because they are representative of choice. While such a metric may be calculated relatively easily for a state machine model that has logical OR semantics, it is not valid for a dependency model. In order to support the calculation of a flexibility metric, there is a need to isolate the AND versus OR relationships in a dependency model, as shown in the example in Fig. 8. The representation of logical structure in a dependency model will be discussed in the following section.

IV. LOGICAL DEPENDENCY STRUCTURE IN A C-DSM

In order to support the representation and estimation of flexibility in a C-DSM model, we extend the C-DSM model with the specification of logical dependency structures. For each node i within the C-DSM, a logical dependency structure may be added to specify the logical relationship among the nodes that influence i .

For example, the endurance node in the dependency model shown in Fig. 7 will be augmented with the following logical dependency structure:

$$(insert\ battery\ 1) \wedge (insert\ battery\ 2 \vee remove\ battery\ 2) \quad (1)$$

Such a specification augments the conventional dependency model by specifying the logical way in which the dependencies combine. For the endurance example, inserting battery 1 and either inserting or removing battery 2 will enable the objective of achieving the required endurance performance.

The specification of logical dependencies enables the identification and estimation of flexibilities. As discussed above, flexibility is captured by the logical OR relationships. Therefore, isolating the OR relationships in the logical dependency structure is necessary to calculate a flexibility metric in dependency models. This is accomplished by transforming the logical dependency structure to the canonical Disjunctive Normal Form (DNF) as discussed in the following section.

V. METRICS FOR FLEXIBILITY AND OPTIONABILITY IN A LOGICAL C-DSM MODEL

The specification of logical dependencies enables the estimation of flexibility and optionability from a C-DSM model. In this section, a flexibility metric is devised based on isolating the OR relationships in the logical dependency structure. An optionability metric is devised to indicate the number of options enabled by the implementation of a mechanism.

A. Flexibility Metric for Dependency Models

Our goal is to isolate the OR relationships in a logical dependency structure, in order to devise a flexibility metric for dependency models. Our approach is to transform the logical dependency structure into the canonical Disjunctive Normal Form (DNF).

Definition: DNF is a logical formula consisting of disjunction of conjunctions where no conjunction contains a disjunction [11].

Mathematically, a formula F is in DNF iff

$$F = \left(\bigvee_{i=1}^n \left(\bigwedge_{j=1}^{m_i} L_{i,j} \right) \right) \quad (2)$$

where $L_{i,j}$ is a literal. Any propositional logic formula may be expressed in DNF. For example, the logical dependency structure presented in (1) is expressed as the following DNF:

$$\begin{aligned} &(insert\ battery\ 1 \wedge insert\ battery\ 2) \vee \\ &(insert\ battery\ 1 \wedge remove\ battery\ 2) \end{aligned} \quad (3)$$

Expressing the logical formula as DNF effectively isolates the ORs in the dependency model and enables the calculation of a flexibility metric as follows:

Flexibility metric (Flex) for a node i : Number of terms in the DNF of the logical dependency structure associated with node i .

In DNF, a term refers to the conjunctive portions of the DNF. For the DNF in (3), the terms are:

$$\begin{aligned} &(insert\ battery\ 1 \wedge insert\ battery\ 2), \\ &(insert\ battery\ 1 \wedge remove\ battery\ 2). \end{aligned}$$

Therefore, the flexibility of achieving the endurance objective can be calculated as the number of DNF terms which is two in this case (Fig. 8).

Specification of a logical dependency structure and its expression as DNF effectively transforms the homogenous dependency model in Fig. 7 to the logical form shown in Fig. 8, thereby enabling the representation and calculation of flexibility in the C-DSM dependency model.

Example: Consider another simple dependency model shown in Fig. 9. The model represents a vehicle that is to be used for reaching a destination (objective) through functions (roll, turn left, turn right, fly) provided by various subsystems (wheel, steering wheel, wing). However, the value delivery (reaching the destination) is affected by the uncertainty of encountering potential obstacles.

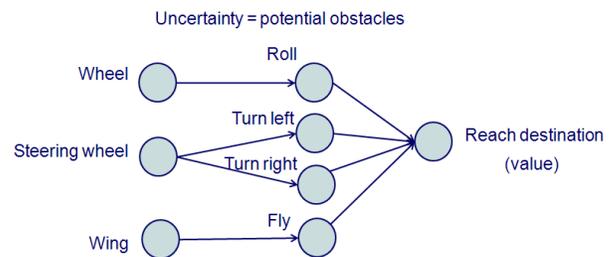


Figure 9. Example dependency model

In order to support flexibility analysis, the dependency model in Fig. 9 may be augmented with a logical dependency structure associated with the “reach destination” objective, expressed in DNF (Fig. 10). Given the logical dependency model in Fig. 10, the flexibility metric may be calculated as the number of terms in the DNF, three in this case.

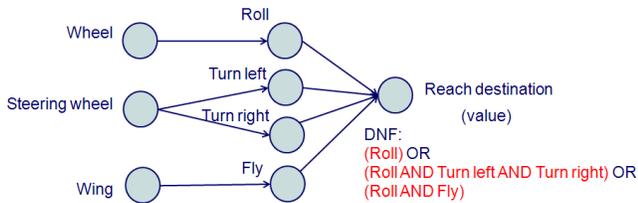


Figure 10. Example of logical dependency model

B. Optionability Metric for Dependency Models

In the above sections we presented a metric for estimating flexibility in dependency models. In this section, we focus on devising a metric for estimating optionability in dependency models. The first step to assessing optionability is to distinguish among the mechanisms and types of options. This is because optionability relates to mechanisms, while flexibility relates to types of options.

Types of options may be identified as nodes that participate in the DNF of a successor node with $Flex > 1$. Mechanisms may be identified as nodes that enable types of options. For the example presented in the previous section, the types of options and mechanisms are identified in Fig. 11.

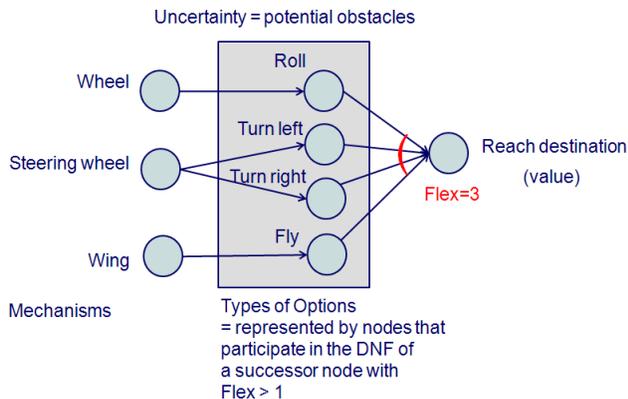


Figure 11. Mechanisms and types of options

The proposed algorithm for calculating an optionability metric for mechanisms is as follows:

1. Group outgoing edges and target nodes from each mechanism being considered into a set S .
2. **Optionability metric (Opt) for a mechanism M :** Number of DNF terms that contain elements of the set S (literals), where the set S is dependent on the mechanism M .

The two steps of the calculation are demonstrated by the examples in Fig. 12 and 13. In Fig. 12, the outgoing edges and nodes for each mechanism are grouped. The Opt metric calculation is shown in Fig. 13. The wheel is a mechanism that enables the option to roll. Since the roll function is contained in three distinct terms of the DNF for “reach destination”, $Opt = 3$ for the wheel mechanism.

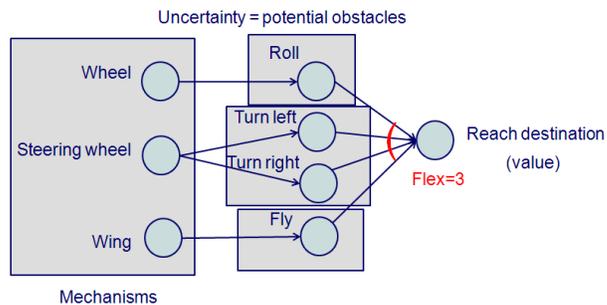


Figure 12. Step 1 of algorithm for calculating optionability metric

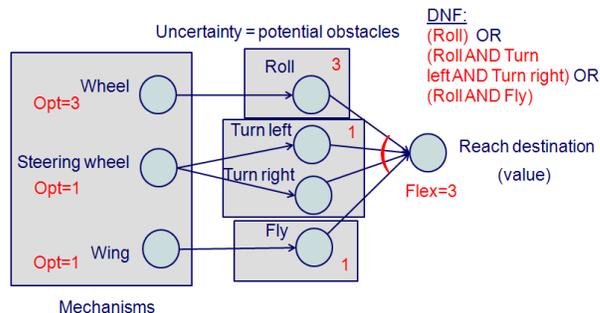


Figure 13. Example of optionability metric (Opt) calculation

For the steering wheel mechanism, the outgoing edges and nodes are grouped, forming the set that contains the turn left and turn right functions. Since turn left and turn right are contained in only a single term within the DNF for “reach destination”, $Opt = 1$ for the steering wheel.

Intuitively, the Opt metric represents the extent to which a given node is optionable, that is the extent to which it enables flexibility. Since a wheel enables the option to roll that is important in providing various different options for reaching the destination, the optionability of the wheel is found to be higher than that of the steering wheel and the wing in this example.

C. Realizability

Although not the focus of this paper, for completeness we present another metric called realizability that arises from the distinction among mechanisms and types of real options. Realizability of an option is defined as the number of different ways that a type of option can be implemented. While optionability indicates the number of alternative option types (actions) enabled by the implementation of a mechanism, realizability indicates the number of alternative mechanisms that can enable a type of option. In the Fig. 11 example, the realizability of each type of option is one, because only a single mechanism enables each type of option.

The calculation of the realizability metric (Rz) is analogous to that of the flexibility metric, because the ORs should be isolated in order to identify the different means of enabling each type of option. Therefore, the specification of a logical dependency model in DNF for each type of option can be used to assess realizability.

VI. RESULTS AND CONCLUSION

In this paper, we presented metrics for estimating flexibility and optionability based on a logical C-DSM model. The logical C-DSM is a new kind of dependency model that includes specification of logical structure among dependencies. The metrics can be used as heuristics to identify real option mechanisms and types that can manage a given uncertainty.

We applied the metrics to an uninhabited air vehicle (UAV) swarm scenario in order to make a purchasing decision under uncertainty. The objective of the UAV swarm is the surveillance of targets at a given revisit rate. However, the revisit rate of the targets, that is the frequency at which targets are observed, is uncertain. The constraint is to maintain communication among neighboring UAVs within the swarm. We modeled this decision problem using a logical C-DSM. The results of applying the metrics to this scenario are summarized in Table 1.

TABLE I. RESULTS OF ESTIMATING ILITIES FOR UAV SWARM SCENARIO

Nodes in logical C-DSM	Ility Metrics		
	Flexibility	Optionability	Realizability
Purchase UAVs with long range comm. sys.	--	2	--
Purchase UAVs with short range comm. sys.	--	1	--
Purchase heterogeneous UAVs (half with long range comm. sys.)	--	2	--
Deploy dense swarm	--	--	3
Deploy sparse swarm	--	--	2
Maintain comm. link and surveillance at an uncertain revisit rate	2	--	--

-- indicates that metric is not calculated.

Note that the metrics are not calculated for every node in the C-DSM. In Table 1, flexibility is estimated for the node representing the objective that is affected by an uncertainty. This leads to the identification of the types of options by backtracking in the C-DSM. The realizability is estimated for the identified types of options. Finally, optionability is estimated for the nodes that influence the identified types of options.

The flexibility metric indicates the presence of an option (flexibility > 1) to manage the uncertainty in the revisit rate and maintain persistent surveillance and communication link. The identified option types are to deploy a sparse swarm or a dense swarm, depending on whether the required revisit rate is high or low. A high revisit rate mission will require the deployment of a dense swarm that provides more frequent observation. For a low revisit rate mission, a sparse swarm consisting of a subset of the UAVs may be able to meet the target revisit rate.

The optionability estimates for alternative purchasing decisions indicate that purchasing a homogeneous swarm with long range communication capability or a heterogeneous swarm with a mix of long and short range communication

systems will enable the option to deploy a dense or sparse swarm. The optionability of purchasing a homogeneous swarm with short range communication system is one, because this alternative does not enable the option to deploy a sparse swarm without violating the network connectivity among neighbors. The alternative purchasing decisions that embed mechanisms to enable options are identified as those with optionability greater than one.

The realizability metric indicates the alternative ways that a type of option may be achieved. For example, deploying a dense swarm can be achieved by purchasing any one of the three alternative swarms.

The calculation of the ility metrics reveals “where” the mechanisms and types of options are embedded. In order to identify whether the investment in any of the mechanisms or options is valuable, we use real options valuation. In the integrated real options framework, we calculate the value of the alternative options under uncertainty by taking into account costs and benefits. The result of real options valuation using a binomial lattice model [2] is that the flexibility to deploy a sparse swarm is worthwhile only when the initial percentage of high revisit rate missions is less than 70%, and that the best way to implement that flexibility is to purchase the UAVs with long range communication system.

In conclusion, we devised metrics to estimate ilities based on a C-DSM model and specification of logical dependencies. The metrics were beneficial in identifying mechanisms and types of real options that can be valued using standard options valuation techniques.

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