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Costing for the Future: Exploring Cost Estimation With Unmanned Autonomous Systems

Ricardo Valerdi, Professor, University of Arizona
CPT Thomas Ryan, Jr., U.S. Army, Professor, U.S. Military Academy

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Panel 18. Forecasting and Controlling Costs in Weapons Systems Procurement

Thursday, May 5, 2016	
1:45p.m. – 3:15 p.m.	**Chair: Todd Calhoun,** Director of Program Assessment & Evaluation, Programs & Resources Department, Headquarters Marine Corps ***Costing Future Complex & Novel Projects*** Michael Pryce, Centre for Defence Acquisition, Cranfield University ***Controlling Costs: The 6-3-5 Method—Case Studies at NAVSEA and NATO*** Bruce Nagy, President/CEO, Catalyst Technologies Morgan Ames, Senior Advisor, Catalyst Technologies ***Costing for the Future: Exploring Cost Estimation With Unmanned Autonomous Systems*** Ricardo Valerdi, Professor, University of Arizona CPT Thomas Ryan, Jr., U.S. Army, Professor, U.S. Military Academy

Costing for the Future: Exploring Cost Estimation With Unmanned Autonomous Systems

Ricardo Valerdi—is an Associate Professor in the University of Arizona's Department of Systems and Industrial Engineering. His research focuses on cost estimation of complex systems, test & evaluation, human systems integration, enterprise transformation, and performance measurement. Dr. Valerdi is Editor-in-Chief of the *Journal of Cost Analysis and Parametrics*, served on the Board of Directors of the International Council on Systems Engineering, and is a Senior Member of IEEE. [rvalerdi@arizona.edu]

CPT Thomas R. Ryan, Jr., U.S. Army—is an Officer in the U.S. Army with a Master of Science in Systems and Industrial Engineering and will be an instructor in the United States Military Academy's Department of Systems Engineering. His research interests are STEM education, cost estimation of complex systems, and human systems integration. He served in both Iraq and Afghanistan as an Infantry Officer and brings a unique perspective, user and customer, to estimation of unmanned systems.

Abstract

Cost, schedule, and quality may not drive a technology, but they shape the chances of that technology becoming actualized. In recent years, the DoD, one of the leading customers of unmanned systems, has continued to struggle with management of cost and schedule causing programs to deliver products that are "good enough," delayed months to years, or even worse, decommissioned. Cost estimation techniques in use today are vast and based on techniques unrelated to emergent systems. One of the most prevalent requirements in the unmanned systems arena is autonomy. The acquisition community will need to adopt new methods for estimating the total cost of ownership of this new breed of systems. Singularly applying traditional software and hardware cost models do not provide this capability because the systems that were used to create and calibrate these models were not Unmanned Autonomous Systems (UMASs; Valerdi, Merrill, & Maloney, 2013). Autonomy, although not new, will redefine the entire way in which estimates are derived. The goal of this paper is to provide a method that attempts to account for how cost estimating for autonomy is different than current methodologies and to suggest ways it can be addressed through the integration and adaptation of existing cost models.

Introduction

Life Cycle Models

When designing a product, the recommended practice is to consider design decisions and their impact throughout the entire life cycle. This is a holistic approach that allows the engineer to examine all phases, and ensure that the stakeholders' (e.g., operators, testers, and maintainers) needs are met (Blanchard & Fabrycky, 2010). This is the same approach that should be taken when identifying product costs, thinking holistically throughout the life cycle. For purposes of discussing the realm of Unmanned Autonomous Systems (UMASs) we focus on two life cycle standards: DoD 5000 (Hagan, 2011; Mills, 2014) and ISO/IEC 15288 Systems Engineering—System Life Cycle Processes (ISO/IEC, 2002).

Both product life cycle standards are organized into discrete phases. Each phase has a distinct role in the life cycle and helps separate major milestones throughout the life cycle of a product. These life cycle stages help answer the "when" and are useful in identifying development, production, and operational costs.

DoD 5000 Acquisition Life Cycle

Although there are many commercial customers being identified and pursued within the UMAS arena, the largest acquirer of autonomous systems is the DoD. The DoD 5000 is a useful framework to apply to a product, as it forces engineers to produce specific sub-products in each of the five phases (Hagan, 2011):

1. In the first phase, Materiel Solution Analysis, the DoD requires an initial capabilities document and an analysis of alternatives study.
2. During the second phase, Technology Development, the goals are to produce a demonstrable prototype that will allow the customer to make decisions in the risk, technology, and design.
3. The third phase, Engineering and Manufacturing Development, forces the engineer to again demonstrate prototype articles, conduct integrated testing (Developmental, Operational, and Live Fire Test and Evaluation), Prepare for both the Critical Design Review and the proposal for product continuation.
4. During the fourth phase, Production and Deployment, engineers are now preparing low-rate and full scale production.
5. The final phase, Operations and Support, consists of activities such as maintaining capabilities, logistical support, upgrades, customer satisfaction, and prepare for proper disposal.

The five phases and major milestones are shown in Figure 1.

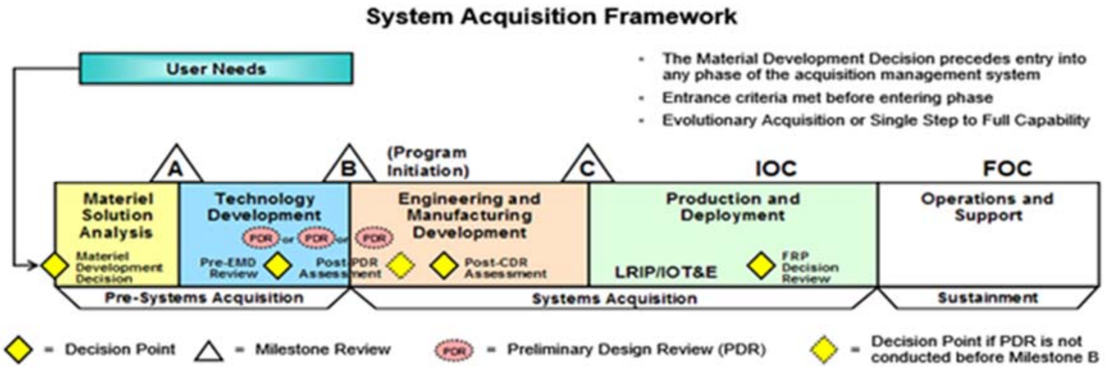


Figure 1. **DoD 5000 Acquisition Framework**
(Spainhower, 2003)

ISO 15288 Life Cycle

A definition of the system life cycle phases is needed to help define the boundaries between engineering activities. A useful standard is ISO/IEC 15288 Systems Engineering System Life Cycle Processes (ISO/IEC 15288). However, the phases established by ISO/IEC 15288 were slightly modified to reflect the influence ANSI/EIA 632 Processes for Engineering a System has on COSYSMO's System Life Cycle Phases, and are shown in Figure 2.

Figure 2. COSYSMO System Life Cycle Phases

Life cycle models vary according to the nature, purpose, use, and prevailing circumstances of the product. Despite an infinite variety in system life cycle models, there is an essential set of characteristic life cycle phases that exists for use in the systems engineering domain.

1. The Conceptualize stage focuses on identifying stakeholder needs, exploring different solution concepts, and proposing candidate solutions.
2. The Development stage involves refining the system requirements, creating a solution description, and building a system.
3. The Operational Test & Evaluation stage involves verifying/validating the system and performing the appropriate inspections before it is delivered to the user.
4. The Operate, Maintain, or Enhance involves the actual operation and maintenance of the system required to sustain system capability.
5. The Replace or Dismantle stage involves the retirement, storage, or disposal of the system.

We revisit these life cycle models later in this section and decompose various types of costs into their respective phases to demonstrate Total Cost of Ownership.

Cost Estimation Methods

The exploration of new cost modeling methods involves the understanding of the cost metrics relevant to the UMAS as well as an understanding of their sensitivity to cost from a production and operational standpoint. In this light, this section provides an overview of different cost estimation approaches used in industry and government. Significant work has been done to understand the costs of aircraft manufacturing (Cook & Grasner, 2001; Markish, 2002; Martin & Evans, 2000) but these studies only deal with manned commercial and military aircraft. Nevertheless, they provide useful insight on how one could approach the estimation of the UMAS life cycle cost.

Case Study and Analogy

Recognizing that companies do not constantly reinvent the wheel every time a new project comes along, there is an approach that capitalizes on the institutional memory of an organization to develop cost estimates. Case studies represent an inductive process whereby estimators and planners try to learn useful general lessons by extrapolation from specific examples. They examine in detail elaborate studies describing the environmental conditions and constraints that were present during the development of previous projects, the technical and managerial decisions that were made, and the final successes or failures that resulted. They then determine the underlying links between cause and effect that can be applied in other contexts. Ideally, they look for cases describing projects similar to the project for which they will be attempting to develop estimates and apply the rule of analogy that assumes previous performance is an indicator of future performance. The sources of case studies may be either internal or external to the estimator's own organization. Home-grown cases are likely to be more relevant for the purposes of estimation because they reflect the specific engineering and business practices likely to be applied to an organization's projects in the future. Well-documented case studies from other organizations doing similar kinds of work can also prove very useful so long as their differences are identified.

Bottom-Up & Activity-Based

Bottom-up estimating begins with the lowest level cost component and rolls it up to the highest level for its estimate. The main advantage is that the lower level estimates are typically provided by the people who will be responsible for doing the work. This work is typically represented in the form of subsystem components, which makes this estimate easily justifiable because of their close relationship to the activities required by each of the system components. This approach also allows for different levels of detail for each component. For example, the costs of an airplane can be broken down into seven main components: center-body, wing, landing gear, propulsion, systems, payloads, and assembly. Each of these components, such as the wing, can be decomposed into subcomponents such as winglet, outer wing, and inner wing. This decomposition is illustrated in more detail in Figure 3. This can translate to a fairly accurate estimate at the lower level components. The disadvantages are that this process is labor intensive and is typically not uniform across products. In addition, every level introduces another layer of conservative management reserve which can result in an overestimate at the end.

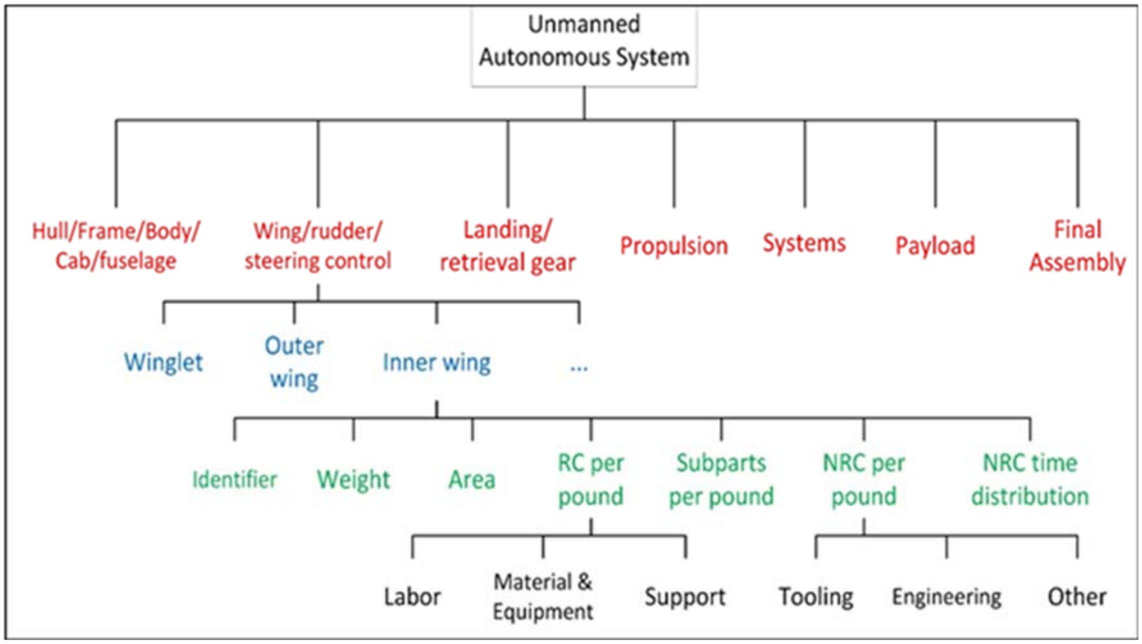


Figure 3. Product Breakdown Structure of a Typical UMAS

Parametric Modeling

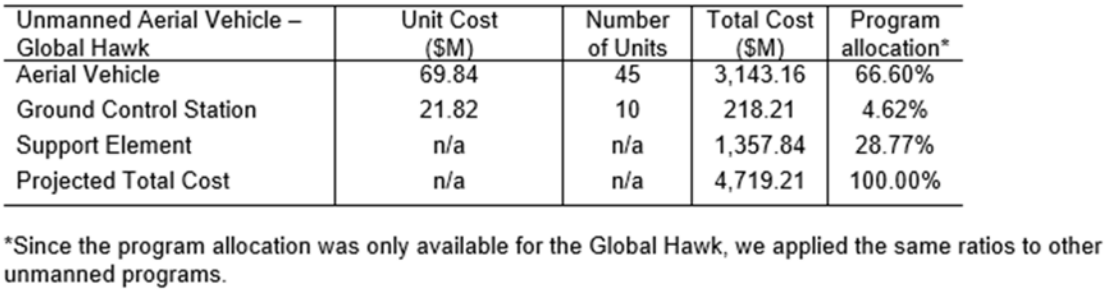
This method is the most sophisticated and most time consuming to develop but often provides the most accurate result. Parametric models generate cost estimates based on mathematical relationships between independent variables (i.e., requirements) and dependent variables (i.e., effort or cost). The inputs characterize the nature of the work to be done, plus the environmental conditions under which the work will be performed and delivered. The definition of the mathematical relationships between the independent and dependent variables is the heart of parametric modeling. These relationships are commonly referred to as cost estimating relationships (CERs) and are usually based upon statistical analyses of large amounts of data. Regression models are used to validate the CERs and operationalize them in linear or nonlinear equations. The main advantage of using parametric models is that, once validated, they are fast and easy to use. They do not require a lot of information and can provide fairly accurate estimates. Parametric models can also be tailored to a specific organization's characteristics such as productivity rates, salary structures, and work breakdown structures. The major disadvantage of parametric models is that they are difficult and time consuming to develop and require a lot of clean, complete, and recent data to be properly validated. Despite the wide range of estimation approaches available for commercial and military aircraft, no parametric models have been created specifically for a UMAS. This could be attributed to the fact that UMASs have not been around for very long and, as a result, there are insufficient data available to validate such models. Before proposing a framework for such a model, unique issues pertaining to the UMAS life cycle are discussed.

UMAS Product Breakdown Structure

It is widely recognized that creating a work breakdown structure (WBS) or product breakdown structure (PBS) is the most complete way to describe a project (Larson, 1952). The level of detail required to properly utilize, or manage with, the PBS such as the one shown in Figure 3 is a crucial component to assigning costs to a product's subcomponents. In this section, we discuss some of the commonalities and shared considerations of designing a WBS/PBS within an unmanned system at the system level. Budgeted amounts for various unmanned and autonomous systems are shown in Tables 1–4 at the 2nd or 3rd level of a WBS/PBS.

Table 1. Air System (UAS)

(DoD, 2014a)

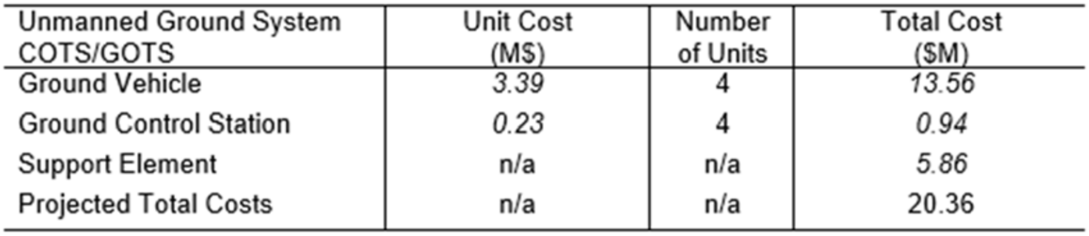


Unmanned Aerial Vehicle – Global Hawk	Unit Cost ($M)	Number of Units	Total Cost ($M)	Program allocation*
Aerial Vehicle	69.84	45	3,143.16	66.60%
Ground Control Station	21.82	10	218.21	4.62%
Support Element	n/a	n/a	1,357.84	28.77%
Projected Total Cost	n/a	n/a	4,719.21	100.00%

*Since the program allocation was only available for the Global Hawk, we applied the same ratios to other unmanned programs.

Table 2. Ground System (UGS)

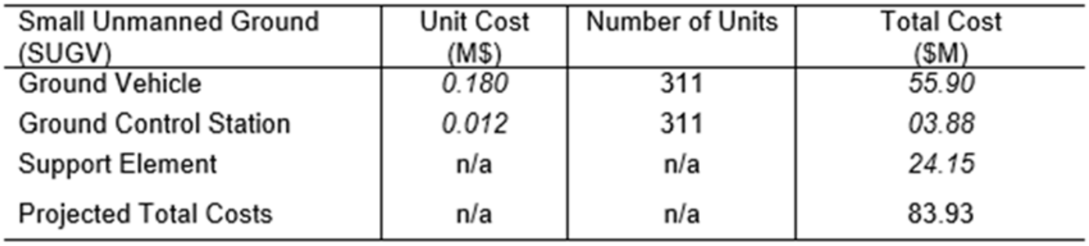
(DoD, 2014b)



Unmanned Ground System COTS/GOTS	Unit Cost (M$)	Number of Units	Total Cost ($M)
Ground Vehicle	*3.39*	4	*13.56*
Ground Control Station	*0.23*	4	*0.94*
Support Element	n/a	n/a	*5.86*
Projected Total Costs	n/a	n/a	20.36

Table 3. Ground System (UGS)

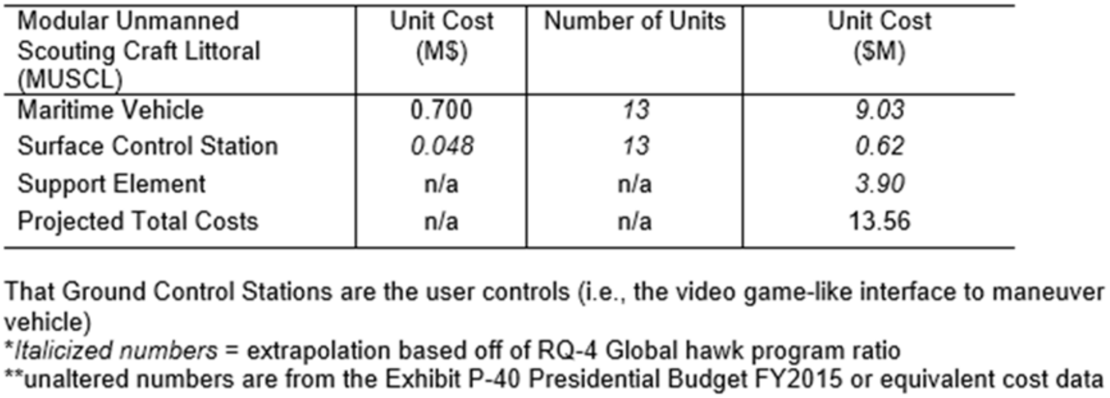
(DoD, 2014b)



Small Unmanned Ground (SUGV)	Unit Cost (M$)	Number of Units	Total Cost ($M)
Ground Vehicle	*0.180*	311	*55.90*
Ground Control Station	*0.012*	311	*03.88*
Support Element	n/a	n/a	*24.15*
Projected Total Costs	n/a	n/a	83.93

Table 4. Marine System (UGS)

(DoD, 2014c)



Modular Unmanned Scouting Craft Littoral (MUSCL)	Unit Cost (M$)	Number of Units	Unit Cost ($M)
Maritime Vehicle	0.700	*13*	*9.03*
Surface Control Station	*0.048*	*13*	*0.62*
Support Element	n/a	n/a	*3.90*
Projected Total Costs	n/a	n/a	13.56

That Ground Control Stations are the user controls (i.e., the video game-like interface to maneuver vehicle)

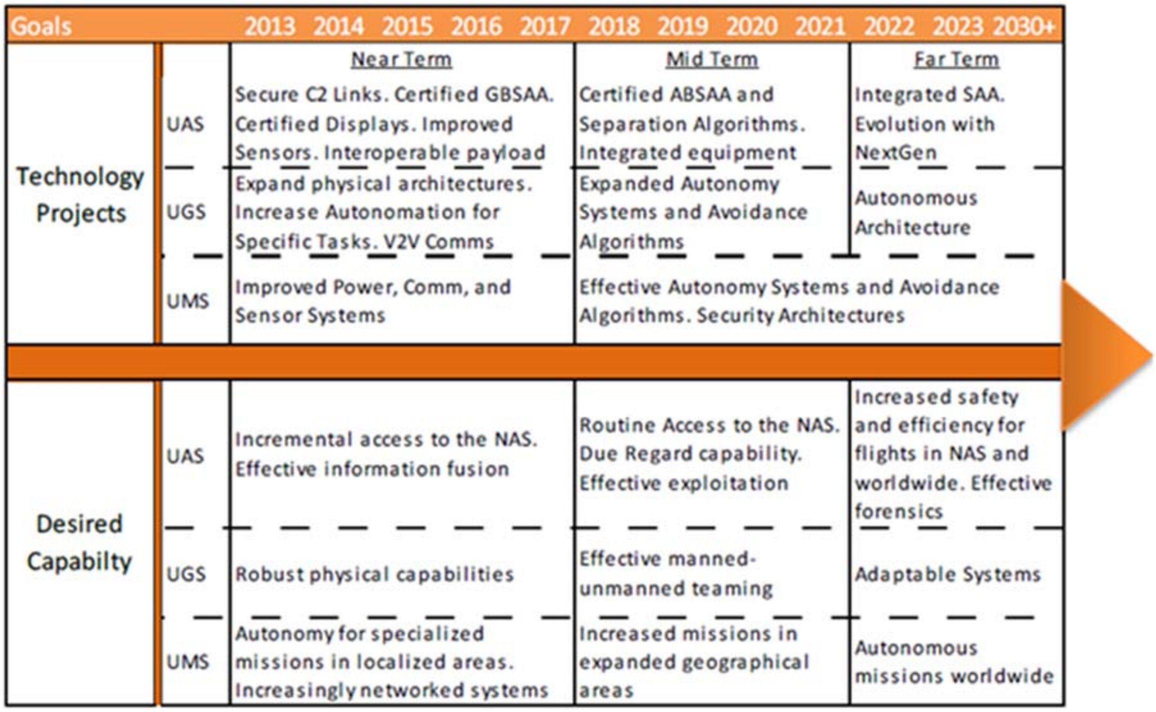
**Italicized numbers* = extrapolation based off of RQ-4 Global hawk program ratio

**unaltered numbers are from the Exhibit P-40 Presidential Budget FY2015 or equivalent cost data

One observation from the UMAS examples provided in Tables 1–4 is the range of unit costs. On the high end, the Flyaway Unit Cost of the Global Hawk Unmanned Aircraft System is $92.87 million (DoD, 2014a, p. 177). On the low end, the Modular Unmanned Scouting Craft Littoral is $700,000 (DoD, 2014c). Another observation from these examples is the wide range of units purchased; as few as four COTS/GOTS packages to convert manned systems to unmanned and as many as 311 Small Unmanned Ground Systems (DoD, 2014b).

Special Considerations

The unique physical and operational characteristics of UMASs require special consideration when exploring cost modeling approaches. In Figure 4, the DoD has laid out its desires for the UMAS over the next 30 years. The DoD has organized its requirements by air, ground, and maritime operational environments, as well as projected the types of exploration initiatives that should allow for success of these autonomous systems. Figure 4 is not meant to be totally exhaustive, but to guide the general direction of the military's UMAS vision.



Goals		2013 2014 2015 2016 2017	2018 2019 2020 2021	2022 2023 2030+
		Near Term	Mid Term	Far Term
Technology Projects	UAS	Secure C2 Links. Certified GBSAA. Certified Displays. Improved Sensors. Interoperable payload	Certified ABSAA and Separation Algorithms. Integrated equipment	Integrated SAA. Evolution with NextGen
	UGS	Expand physical architectures. Increase Autonomation for Specific Tasks. V2V Comms	Expanded Autonomy Systems and Avoidance Algorithms	Autonomous Architecture
	UMS	Improved Power, Comm, and Sensor Systems	Effective Autonomy Systems and Avoidance Algorithms. Security Architectures	
Desired Capabilty	UAS	Incremental access to the NAS. Effective information fusion	Routine Access to the NAS. Due Regard capability. Effective exploitation	Increased safety and efficiency for flights in NAS and worldwide. Effective forensics
	UGS	Robust physical capabilities	Effective manned-unmanned teaming	Adaptable Systems
	UMS	Autonomy for specialized missions in localized areas. Increasingly networked systems	Increased missions in expanded geographical areas	Autonomous missions worldwide

Figure 4. **Operating Environment Technology Development Timeline (2013–2030)** (DoD, 2013)

Mission Requirements (DoD, 2013)

The mission requirements are specified tasks with which the UMAS must comply in order to perform. These requirements are shaped by the operational environment (OE), or venue by which the UMAS will perform its intended functions or capabilities that can be physical and situational. The physical environment can consist of air, ground (surface and sub-surface), and marine (surface and submersible.)

System Capabilities

In essence, what will the UMAS do for the customer? These functions must also include current capabilities such as attack, logistical, and reconnaissance. This area also includes any of the "-ilities" that a UMAS might need to adhere to that are not specified in its mission requirements. These may include manufacturability, reliability, interoperability, survivability, and maintainability.

Payloads

A final consideration for the UMAS is its payload. This could also be categorized as special equipment. For example, a logistical UMAS (or cargo transportation system like the SMSS™) needs to have a tow system or recovery package in addition to the ground vehicle; or if it is an attack/reconnaissance system—it needs to support munitions, missiles, or gun platforms.

Although many more areas can be identified for consideration when engineering a system for autonomy, this section was meant to highlight the WBS/PBS in more detail rather than the technical capabilities of the UMAS itself. The cost to build and produce a system is a bottom line decision for the producer (and the engineer), but the DoD needs and expects that a WBS represent all phases of the life cycle. By accurately representing the system in a more complete WBS/PBS, the cost estimates will have more fidelity and a higher confidence, because estimators will be able to link the lowest level of that structure to a group of cost drivers within a cost model.

Cost Drivers and Parametric Cost Models

Cost drivers are characteristics of projects that best capture the effort, typically measured in Person Months, required to complete them (Boehm, 2000). As mentioned in the Parametric Modeling section, developing these characteristics, or drivers, is data and labor intensive. The developer of the model must establish a strong mathematical relationship, usually a form of regression, between an identified characteristic and its impact on the project. The number of cost drivers for each type of estimate will vary according to the type of component (hardware, software, etc.).

Each cost driver has a scale, usually of five levels, which allows the user of the model to best represent characteristics of the product. For example, a cost driver can be described using Very Low, Low, Nominal, High, or Very High—each one of these choices has a value that will either increase or decrease cost (Valerdi, 2008). Each level is clearly defined so the user can estimate the complexity of a system as realistically as possible. The key for success with utilizing parametric modeling and its drivers is to fully understand and be realistic with assignment of scale values.

Cost Drivers for Estimating Development Costs

Our proposed method for system level estimation is to combine five different parametric models that best represent the amount of effort required to successfully build, test, produce, and operate an Unmanned Autonomous System (UMAS). These include (1) Hardware, (2) Software, (3) Systems Engineering and Program Management, (4) Performance-Based Characteristics, and (5) Weight-Based Characteristics.

Each of the five models is subsequently described and should be considered when developing a complete life cycle estimate; however, it is not mandatory to utilize all five since each UMAS will have unique cost and performance considerations.

Hardware

SEER-H is a hybrid model that utilizes analogous estimates, as well as harnessing parametric mathematical cost estimation relationships specific to hardware products. SEER-H aids in the estimation of hardware development, production, and operations costs (SEER-H® Documentation Team: MC, WL, JT, KM, 2014). Unlike the other estimation tools available, SEER-H has an exhaustive suite and could be used to estimate many technical areas. The number of cost drivers in SEER-H is extensive; therefore we focus on only three within the Mechanical/Structural Work Elements category:

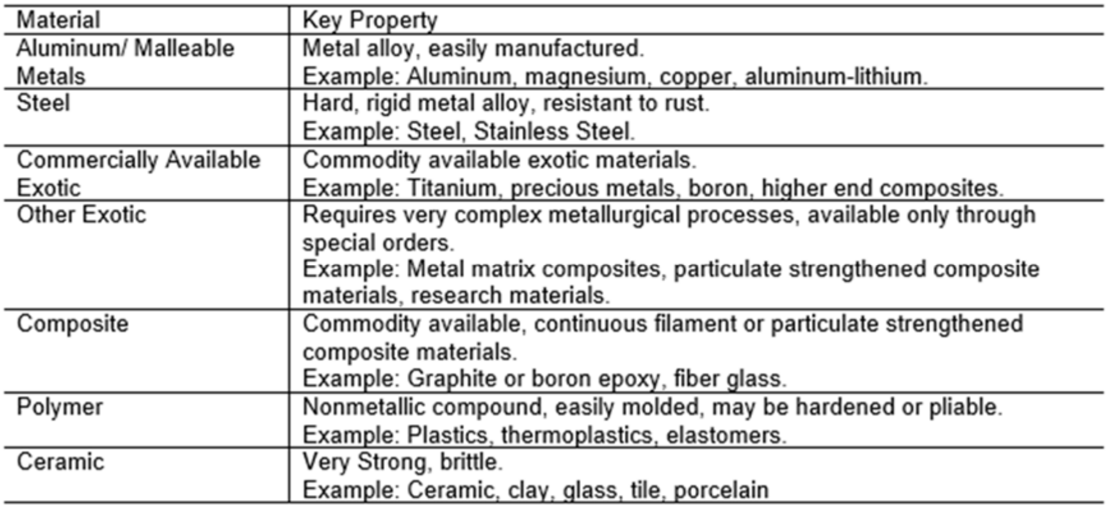
- Material Composition—the material that will dominate the system and its difficulty to acquire
- Certification Level—the amount of Test & Evaluation with demonstration required for the materials utilized
- Production Tools and Practices—how ready the materials are for production

Material Composition

This SEER-H driver is categorized by the predominant material used to build the system, sub-system, or the system’s components, as shown in Table 5. The estimator should also consider some of the materials that may not dominate, but are identified as critical. The total cost may be a combination of critical and dominant materials.

Table 5. Material Composition Rating Scale

(SEER-H® Documentation Team, 2014)



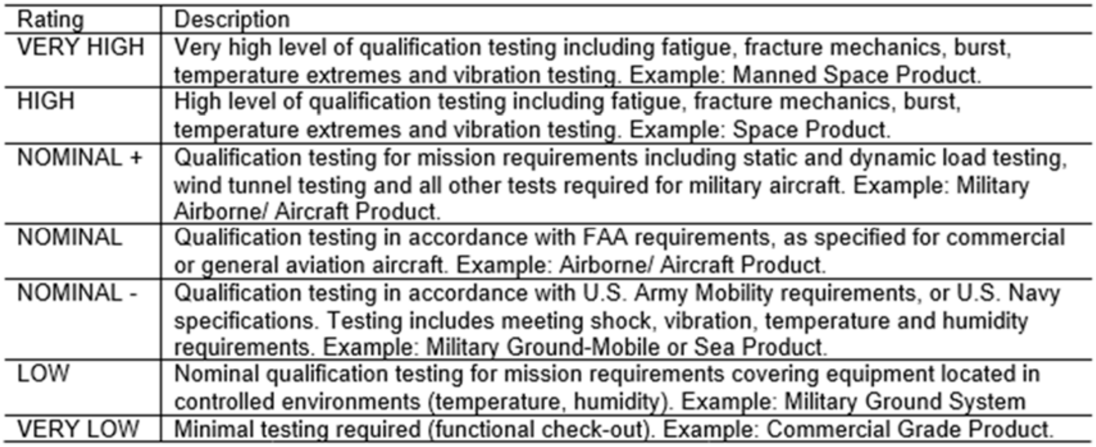
Material	Key Property
Aluminum/ Malleable Metals	Metal alloy, easily manufactured. Example: Aluminum, magnesium, copper, aluminum-lithium.
Steel	Hard, rigid metal alloy, resistant to rust. Example: Steel, Stainless Steel.
Commercially Available Exotic	Commodity available exotic materials. Example: Titanium, precious metals, boron, higher end composites.
Other Exotic	Requires very complex metallurgical processes, available only through special orders. Example: Metal matrix composites, particulate strengthened composite materials, research materials.
Composite	Commodity available, continuous filament or particulate strengthened composite materials. Example: Graphite or boron epoxy, fiber glass.
Polymer	Nonmetallic compound, easily molded, may be hardened or pliable. Example: Plastics, thermoplastics, elastomers.
Ceramic	Very Strong, brittle. Example: Ceramic, clay, glass, tile, porcelain

Certification Level

Certification level represents the requirements imposed on the manufacturer by the customer, as shown in Table 6. This parameter quantifies the additional cost associated with the customer's certification requirements; therefore, any extra certification, inspections, or intangible property security controls, etc., will increase cost.

Table 6. Certification Level Rating Scale

(SEER-H® Documentation Team, 2014)



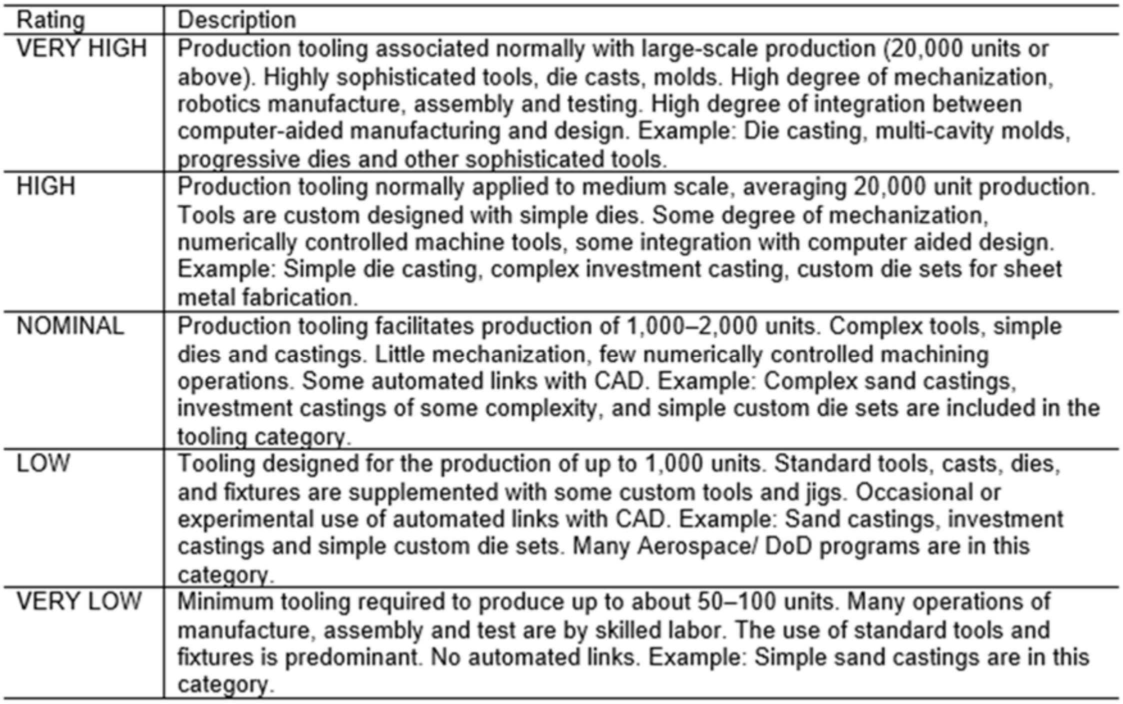
Rating	Description
VERY HIGH	Very high level of qualification testing including fatigue, fracture mechanics, burst, temperature extremes and vibration testing. Example: Manned Space Product.
HIGH	High level of qualification testing including fatigue, fracture mechanics, burst, temperature extremes and vibration testing. Example: Space Product.
NOMINAL +	Qualification testing for mission requirements including static and dynamic load testing, wind tunnel testing and all other tests required for military aircraft. Example: Military Airborne/ Aircraft Product.
NOMINAL	Qualification testing in accordance with FAA requirements, as specified for commercial or general aviation aircraft. Example: Airborne/ Aircraft Product.
NOMINAL -	Qualification testing in accordance with U.S. Army Mobility requirements, or U.S. Navy specifications. Testing includes meeting shock, vibration, temperature and humidity requirements. Example: Military Ground-Mobile or Sea Product.
LOW	Nominal qualification testing for mission requirements covering equipment located in controlled environments (temperature, humidity). Example: Military Ground System
VERY LOW	Minimal testing required (functional check-out). Example: Commercial Grade Product.

Production Tools and Practices

This parameter describes the extent to which efficient fabrication methodologies and processes are used, and the automation of labor-intensive operations. The rating should reflect the state of production tools that are in place and already being used by the time hardware production begins (see Table 7).

Table 7. Production Tools and Practices Rating Scale

(SEER-H® Documentation Team, 2014)



Rating	Description
VERY HIGH	Production tooling associated normally with large-scale production (20,000 units or above). Highly sophisticated tools, die casts, molds. High degree of mechanization, robotics manufacture, assembly and testing. High degree of integration between computer-aided manufacturing and design. Example: Die casting, multi-cavity molds, progressive dies and other sophisticated tools.
HIGH	Production tooling normally applied to medium scale, averaging 20,000 unit production. Tools are custom designed with simple dies. Some degree of mechanization, numerically controlled machine tools, some integration with computer aided design. Example: Simple die casting, complex investment casting, custom die sets for sheet metal fabrication.
NOMINAL	Production tooling facilitates production of 1,000–2,000 units. Complex tools, simple dies and castings. Little mechanization, few numerically controlled machining operations. Some automated links with CAD. Example: Complex sand castings, investment castings of some complexity, and simple custom die sets are included in the tooling category.
LOW	Tooling designed for the production of up to 1,000 units. Standard tools, casts, dies, and fixtures are supplemented with some custom tools and jigs. Occasional or experimental use of automated links with CAD. Example: Sand castings, investment castings and simple custom die sets. Many Aerospace/ DoD programs are in this category.
VERY LOW	Minimum tooling required to produce up to about 50–100 units. Many operations of manufacture, assembly and test are by skilled labor. The use of standard tools and fixtures is predominant. No automated links. Example: Simple sand castings are in this category.

Software

The recommended parametric estimation tool for UMAS software aspects is the Constructive Cost Model (COCOMO II). This model has 30 years of refinement, and is an industry and academic standard for parametric modeling (Boehm, 2000). The number of cost drivers in COCOMO II vary from 7 to 17 depending on the life cycle phase of the project in which the estimate is being performed (Boehm, 2000). Since less information is known at the beginning of the project, the COCOMO II model provides fewer parameters to rate. As more information is known about the software project, the number of parameters increases. This section is not meant to replace the COCOMO II User's Manual,[1] but rather provide relevant details about the relevant cost drivers. Three drivers are relevant for UMAS software estimation:

- Size—measured by number of lines of lode
- Team Cohesion—weighted average of four characteristics
- Programmer Capability—how efficient programmers are as a whole

Size

Size is in units of thousands of source lines of code (KSLOC) is derived from estimating the size of software modules that will constitute the application program. It can also be estimated using unadjusted function points (UFP), converted to SLOC, then divided

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[1] http://csse.usc.edu/csse/research/COCOMOII/cocomo_main.html

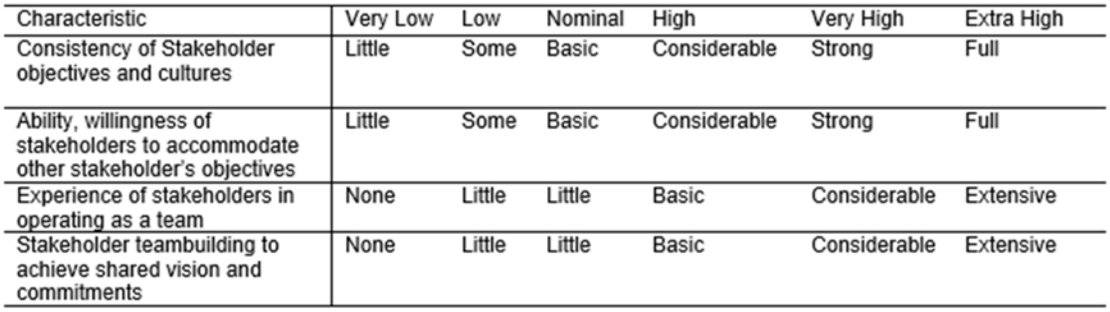
by one thousand. Equation 1 is the basic COCOMO II algorithm which includes Size as the central component to calculating effort in Person Months (PM).

$$PM = A \times (SIZE)^{E} \times \prod_{i=1}^{n} EM_i \qquad (1)$$

Team Cohesion

This parameter accounts for the human component in software design. These elements are not limited to but contain differences in multiple stake-holder objectives, cultural backgrounds, team resiliency, and team familiarity (see Table 8). The focus is how the design team interacts externally within the project.

Table 8. Team Cohesion Rating Scale

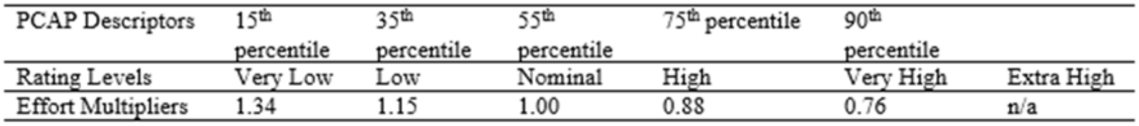


Characteristic	Very Low	Low	Nominal	High	Very High	Extra High
Consistency of Stakeholder objectives and cultures	Little	Some	Basic	Considerable	Strong	Full
Ability, willingness of stakeholders to accommodate other stakeholder's objectives	Little	Some	Basic	Considerable	Strong	Full
Experience of stakeholders in operating as a team	None	Little	Little	Basic	Considerable	Extensive
Stakeholder teambuilding to achieve shared vision and commitments	None	Little	Little	Basic	Considerable	Extensive

Programmer Capability

This parameter also deals with a human aspect of software engineering; however, it differs from team cohesion in the direction of the focus. In this parameter the assessment is on the internal workings of the team's capability as it relates to the team's efficiency, thoroughness, internal communication, and cooperation (see Table 9).

Table 9. Programmer Capability Rating Scale



PCAP Descriptors	15th percentile	35th percentile	55th percentile	75th percentile	90th percentile	
Rating Levels	Very Low	Low	Nominal	High	Very High	Extra High
Effort Multipliers	1.34	1.15	1.00	0.88	0.76	n/a

Systems Engineering and Project Management

To estimate the Systems Engineering and Project Management required effort for a UMAS, we use the Constructive Systems Engineering Cost Model (COSYSMO). This parametric model's output accounts for integrating system components and will quantify intangible efforts such as requirements, architecting, design, verification, and validation (Valerdi, 2008). This model also depends on 18 size and cost drivers.[2] By introducing some of the most important drivers we capture the most important cost considerations of a UMAS. The three most relevant systems engineering cost drivers are as follows:

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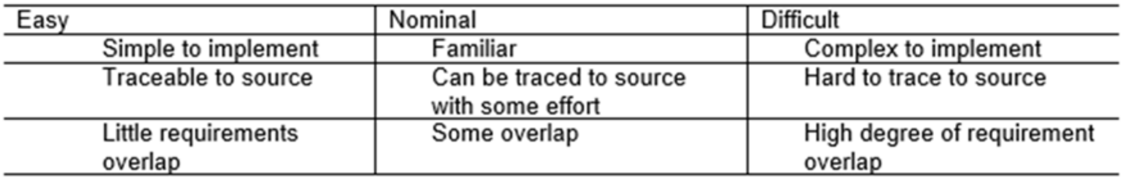
[2] http://cosysmo.mit.edu

- Number of System Requirements—number of specified functions a system must perform to meet the user’s needs
- Technology Risk—how mature or demonstrated the technologies are
- Process Capability—how well/consistent the team/organization performs in terms of the Capability Maturity Model Integration (CMMI)

Number of Requirements

The Number of Requirements parameter asks the estimator to count the number of requirements for the UMAS at a specific level of design (see Table 10). These requirements may deal with number of system interfaces, system specific algorithms, and operational scenarios. Requirements are not limited to but may be functional, performance, feature, or service-oriented in nature depending on the methodology used for specification. Of note, requirement statements usually contain the words “shall,” “will,” “should,” or “may.”

Table 10. Number of Requirements Rating Scale

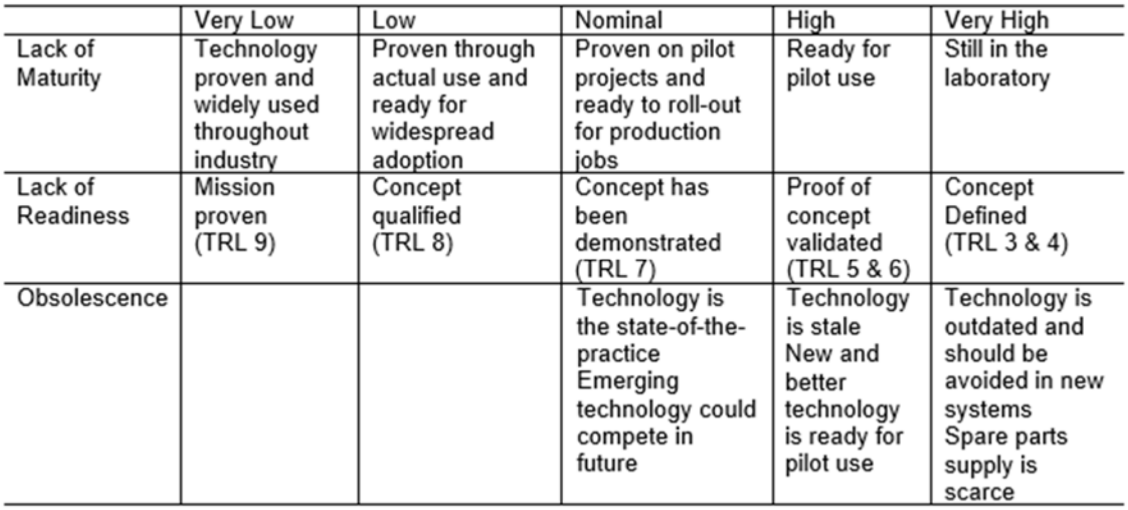


Easy	Nominal	Difficult
Simple to implement	Familiar	Complex to implement
Traceable to source	Can be traced to source with some effort	Hard to trace to source
Little requirements overlap	Some overlap	High degree of requirement overlap

Technology Risk

The Technology Risk parameter asks you to evaluate a UMAS’s sub-system’s maturity, readiness, and obsolescence of the technologies being implemented (see Table 11). Immature or obsolescent technologies will require more systems engineering effort.

Table 11. Technology Risk Rating Scale

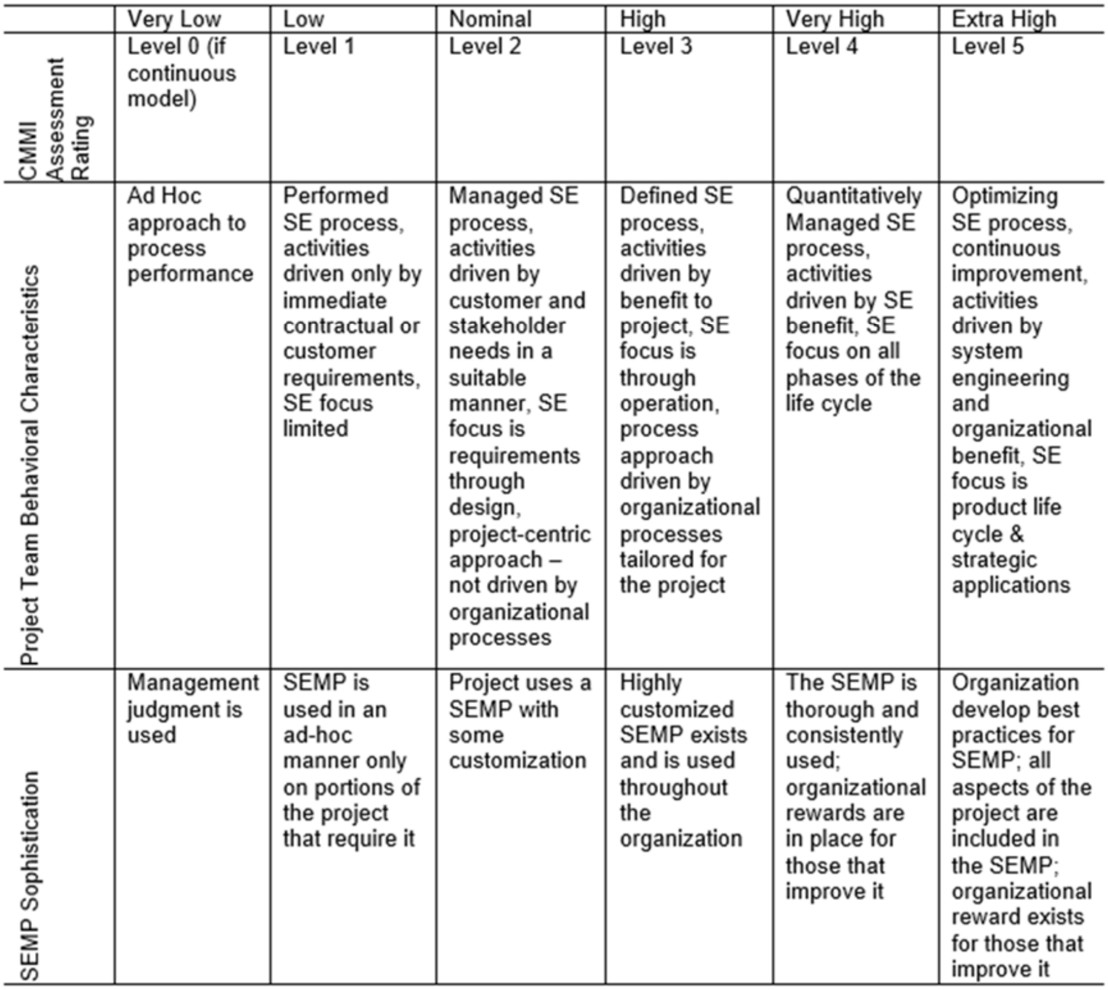


	Very Low	Low	Nominal	High	Very High
Lack of Maturity	Technology proven and widely used throughout industry	Proven through actual use and ready for widespread adoption	Proven on pilot projects and ready to roll-out for production jobs	Ready for pilot use	Still in the laboratory
Lack of Readiness	Mission proven (TRL 9)	Concept qualified (TRL 8)	Concept has been demonstrated (TRL 7)	Proof of concept validated (TRL 5 & 6)	Concept Defined (TRL 3 & 4)
Obsolescence			Technology is the state-of-the-practice Emerging technology could compete in future	Technology is stale New and better technology is ready for pilot use	Technology is outdated and should be avoided in new systems Spare parts supply is scarce

Process Capability

Like some of the COCOMO II parameters, this COSYSMO example focuses on the consistency and effectiveness of a project team performing the systems engineering processes. The assessment of this driver may be based on ratings from a published process model (e.g., CMMI [2002], EIA-731 [ANSI/EIA, 2002], SE-CMM [Boehm, 2000; Clark, 1997], ISO/IEC 15504 [2003, 2012]). It can alternatively be based on project team behavioral characteristics if no previous external assessments have occurred.

Table 12. Process Capability Rating Scale



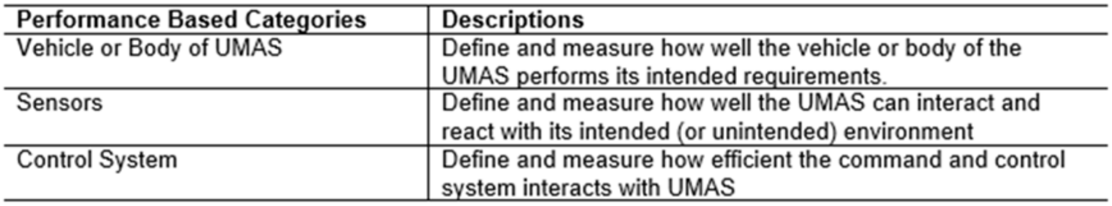
	Very Low	Low	Nominal	High	Very High	Extra High
CMMI Assessment Rating	Level 0 (if continuous model)	Level 1	Level 2	Level 3	Level 4	Level 5
Project Team Behavioral Characteristics	Ad Hoc approach to process performance	Performed SE process, activities driven only by immediate contractual or customer requirements, SE focus limited	Managed SE process, activities driven by customer and stakeholder needs in a suitable manner, SE focus is requirements through design, project-centric approach – not driven by organizational processes	Defined SE process, activities driven by benefit to project, SE focus is through operation, process approach driven by organizational processes tailored for the project	Quantitatively Managed SE process, activities driven by SE benefit, SE focus on all phases of the life cycle	Optimizing SE process, continuous improvement, activities driven by system engineering and organizational benefit, SE focus is product life cycle & strategic applications
SEMP Sophistication	Management judgment is used	SEMP is used in an ad-hoc manner only on portions of the project that require it	Project uses a SEMP with some customization	Highly customized SEMP exists and is used throughout the organization	The SEMP is thorough and consistently used; organizational rewards are in place for those that improve it	Organization develop best practices for SEMP; all aspects of the project are included in the SEMP; organizational reward exists for those that improve it

Performance-Based Cost Estimating Relationship

One important consideration of every product is its ability to perform the specified requirements well. The model that best captures the performance characteristics of a product was created by the Army for Unmanned Aerial Vehicle Systems, but can be modified to fit other autonomous systems (Cherwonik & Wehrley, 2003). The methodologies for estimating performance are not restricted to this list, but should fit in similar categories for air, land, sea, or space (see Table 13).

Table 13. Performance-Based Characteristics Rating Scale

(Cherwonik & Wehrley, 2003)

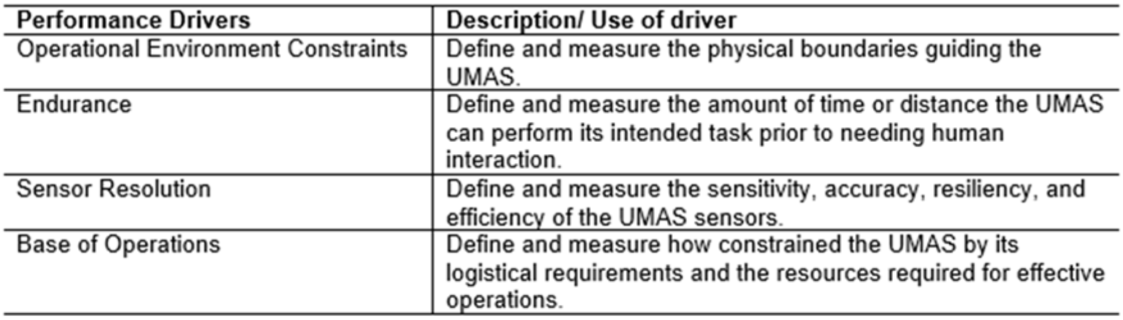


Performance Based Categories	Descriptions
Vehicle or Body of UMAS	Define and measure how well the vehicle or body of the UMAS performs its intended requirements.
Sensors	Define and measure how well the UMAS can interact and react with its intended (or unintended) environment
Control System	Define and measure how efficient the command and control system interacts with UMAS

The cost drivers that are recommended for performance measurement are based on an aerial platform, but are modified in this section to provide ideas on what areas to consider (see Table 14).

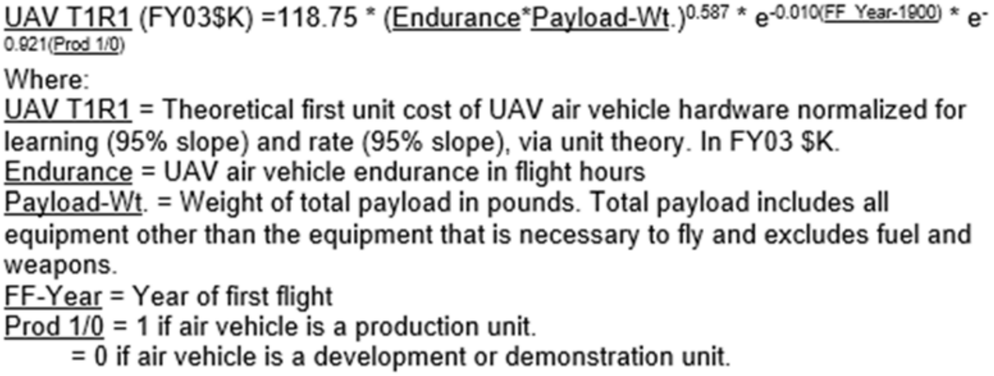
Table 14. Performance Cost Drivers

(Cherwonik & Wehrley, 2003)



Performance Drivers	Description/ Use of driver
Operational Environment Constraints	Define and measure the physical boundaries guiding the UMAS.
Endurance	Define and measure the amount of time or distance the UMAS can perform its intended task prior to needing human interaction.
Sensor Resolution	Define and measure the sensitivity, accuracy, resiliency, and efficiency of the UMAS sensors.
Base of Operations	Define and measure how constrained the UMAS by its logistical requirements and the resources required for effective operations.

The Army's performance-based Cost Estimating Relationship is shown in Equation 2:



$$\underline{\text{UAV T1R1}}\ (\text{FY03\$K}) = 118.75 * (\underline{\text{Endurance}} * \underline{\text{Payload-Wt}}.)^{0.587} * e^{-0.010(\underline{\text{FF Year-1900}})} * e^{-0.921(\underline{\text{Prod 1/0}})}$$

Where:

UAV T1R1 = Theoretical first unit cost of UAV air vehicle hardware normalized for learning (95% slope) and rate (95% slope), via unit theory. In FY03 $K.

Endurance = UAV air vehicle endurance in flight hours

Payload-Wt. = Weight of total payload in pounds. Total payload includes all equipment other than the equipment that is necessary to fly and excludes fuel and weapons.

FF-Year = Year of first flight

Prod 1/0 = 1 if air vehicle is a production unit.
= 0 if air vehicle is a development or demonstration unit.

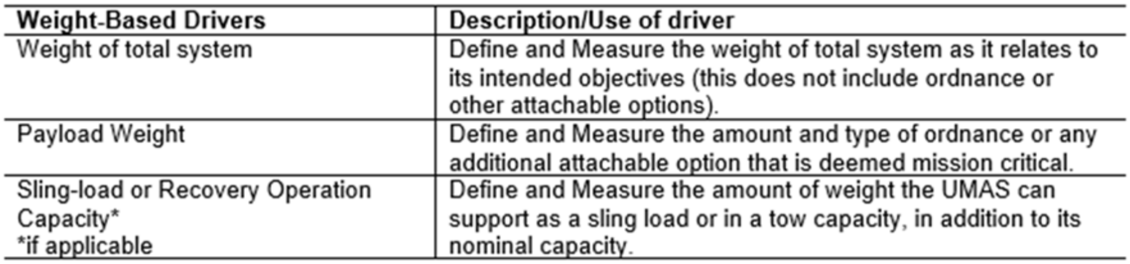
(2)

Weight-Based Cost Estimating Relationship

A final consideration for estimating the cost of the UMAS is its weight. Weight may already exist as an important cost driver in other estimation models such as hardware and performance; however, we feel that this particular estimation relationship is strong enough to also be a stand-alone component. When operational implementation is considered for a given autonomous system, weight plays a critical role in the success or failure. Some drivers, modified from the source to apply to the UMAS, are shown in Table 15.

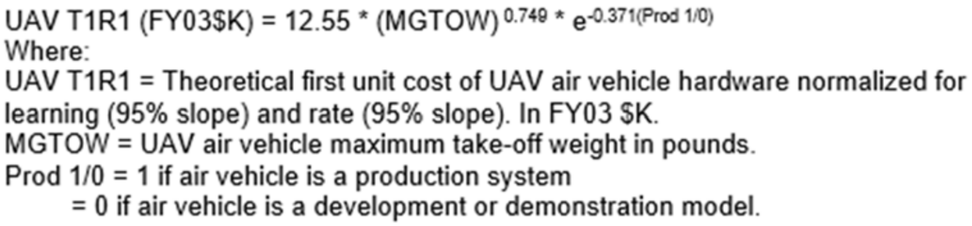
Table 15. Weight-Based Cost Drivers

(Cherwonik & Wehrley, 2003)



Weight-Based Drivers	Description/Use of driver
Weight of total system	Define and Measure the weight of total system as it relates to its intended objectives (this does not include ordnance or other attachable options).
Payload Weight	Define and Measure the amount and type of ordnance or any additional attachable option that is deemed mission critical.
Sling-load or Recovery Operation Capacity* *if applicable	Define and Measure the amount of weight the UMAS can support as a sling load or in a tow capacity, in addition to its nominal capacity.

The Army's weight-based Cost Estimating Relationship is shown in Equation 3:



UAV T1R1 (FY03$K) = 12.55 * $(\text{MGTOW})^{0.749}$ * $e^{-0.371(\text{Prod }1/0)}$
Where:
UAV T1R1 = Theoretical first unit cost of UAV air vehicle hardware normalized for learning (95% slope) and rate (95% slope). In FY03 $K.
MGTOW = UAV air vehicle maximum take-off weight in pounds.
Prod 1/0 = 1 if air vehicle is a production system
= 0 if air vehicle is a development or demonstration model.

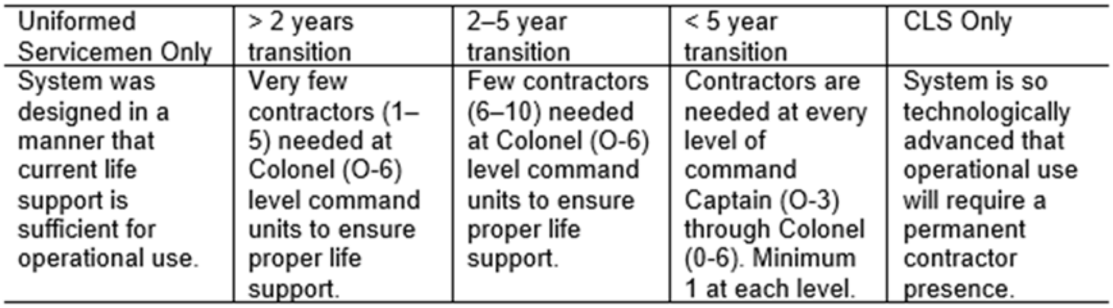
(3)

Proposed Cost Drivers for DoD 5000.02 Phase Operations & Support

Logistics—Transition From Contractor Life Support (CLS) for Life to Organic Capabilities

Managing logistic support is complex and not easy to summarize into a single parameter. However, all systems require maintenance which can be described within the range provided in Table 16. The goal of this parameter is to allow life cycle planners to nest their system engineering plan into DoD requirements and minimize contractor life support.

Table 16. Logistics Cost Driver



Uniformed Servicemen Only	> 2 years transition	2–5 year transition	< 5 year transition	CLS Only
System was designed in a manner that current life support is sufficient for operational use.	Very few contractors (1–5) needed at Colonel (O-6) level command units to ensure proper life support.	Few contractors (6–10) needed at Colonel (O-6) level command units to ensure proper life support.	Contractors are needed at every level of command Captain (O-3) through Colonel (0-6). Minimum 1 at each level.	System is so technologically advanced that operational use will require a permanent contractor presence.

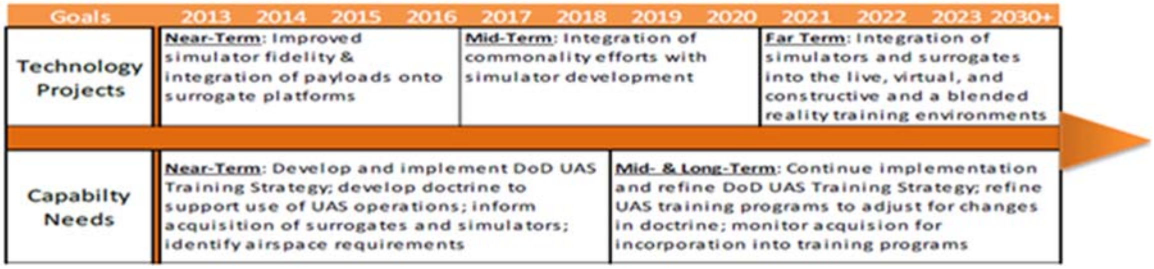
Training

The development costs for a UMAS can be significant, but one area of consideration is how quickly and efficiently users can be trained to employ the system. With the increasing levels of autonomy, this warrants its own cost driver.

Table 17. Training Cost Driver Considerations

Minimal impact	Medium Impact	High Impact	Extreme Impact	Unknown Impact
Training fits current TRADOC[3] through-put. And requires minimal certification (example system is a modified version of a previously integrated systems – autonomous raven)	Training program is similar to a current DoD method; however, needs to be a stand-alone block of instruction or course. Can use existing facilities and infrastructure currently provided.	Training program is not similar to any current DoD method. Needs to be a stand-alone course. Needs facilities and infrastructure not currently provided.	Training program is not similar to any current DoD method. Needs to be a stand-alone course. Needs facilities and infrastructure not currently available.	Training systems are still being developed and will require extensive integration

The planning for and implementation of such training considerations in Table 17 will be challenging. The DoD acknowledges these challenges and offers a perspective of expectation management displayed in Figure 5. The training objectives attempt to lay out how the UMAS and other emergent systems will be inculcated into the existing training system. As engineers build their systems understanding, these strategies will help with system implementation in areas that are not implicitly the system being procured.



Technology Projects

Near-Term: Improved simulator fidelity & integration of payloads onto surrogate platforms

Mid-Term: Integration of commonality efforts with simulator development

Far Term: Integration of simulators and surrogates into the live, virtual, and constructive and a blended reality training environments

Capabilty Needs

Near-Term: Develop and implement DoD UAS Training Strategy; develop doctrine to support use of UAS operations; inform acquisition of surrogates and simulators; identify airspace requirements

Mid- & Long-Term: Continue implementation and refine DoD UAS Training Strategy; refine UAS training programs to adjust for changes in doctrine; monitor acquision for incorporation into training programs

Figure 5. UMAS Training Objectives (2013–2030)
(DoD, 2013)

Operations—Manned Unmanned Systems Teaming (MUM-T)

The goal of the DoD's investment in the UMAS is to enhance the warfighters' capability while reducing risk to human life, maintaining tactical advantage, and performing tasks that can be dull, dirty, or dangerous (DoD, 2013).However, all of the systems will require some level of manned-with-unmanned cooperation. The more these two worlds efficiently work together, the better the operational outcome.

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[3] U.S. Army Training and Doctrine Command

Table 18. Manned Unmanned Systems Teaming Cost Driver

Very Low Teaming	Low Teaming	Nominal Teaming	High Teaming	Very High Teaming
Meets no joint interoperability requirements, and generates data that needs to be transferred to a common operating picture	Meets minimum branch specific interoperability requirements, but is not compatible with all systems employed by its home branch	Meets branch specific interoperability requirements, and shares information with manned systems, branch specific.	Meets all branch specific interoperability requirements, as well as one or more joint requirements. Also shares information with manned systems.	Meets all Joint interoperability requirements, and shares a common operating picture other manned and unmanned systems can utilize

Considerations for Estimating Unmanned Ground Vehicle

For a large scale project that requires the integration of multiple engineering disciplines, specifically in the field of the UMAS, no single estimation tool can completely capture total life cycle costs. By applying the proper estimation models, or a combination of these models, the estimator can ensure complete coverage of each program element and their relative cost impact across the UMAS project life cycle.

The example used to illustrate the cost estimating process is the Lockheed Martin Unmanned Autonomous Ground System, Squad Mission Support System (SMSS™). By utilizing the product work breakdown structure (P-WBS) cost experts can then apply an estimation tool at the appropriate level. The sum of each sub-estimate is then integrated into the overall project level estimation. Considerations for which level within the P-WBS requires estimates is unique to each UMAS project. Contractual requirements will be the determining factor on how detailed the estimate needs to be.

In response to the critical need for lightening, the soldier and marine infantryman's load in combat as well as providing the utility and availability of equipment that could not otherwise be transported by dismounted troops, the Squad Mission Support System is being developed by Lockheed Martin. The SMSS™ can address the requirements of Light Infantry, Marine, and Special Operating Forces to maneuver in complex terrain and harsh environments, carrying all types of gear, materiel, and Mission Equipment Packages (MEP).

The SMSS™ is a squad-sized UGV platform shown in Figure 6, about the size of a compact car, capable of carrying up to 1,500 pounds of payload. Designed to serve as a utility and cargo transport for dismounted small unit operations, it possesses excellent mobility in most terrains. The SMSS™/ Transport lightens the load of a 9–13 man team by carrying their extended mission equipment, food, weapons, and ammunition on unimproved roads, in urban environments, and on cross-country terrain. Control modes include tethered, radio control, teleoperation (NLOS and BLOS), supervised autonomy, and voice command. TRL level is 7–9.

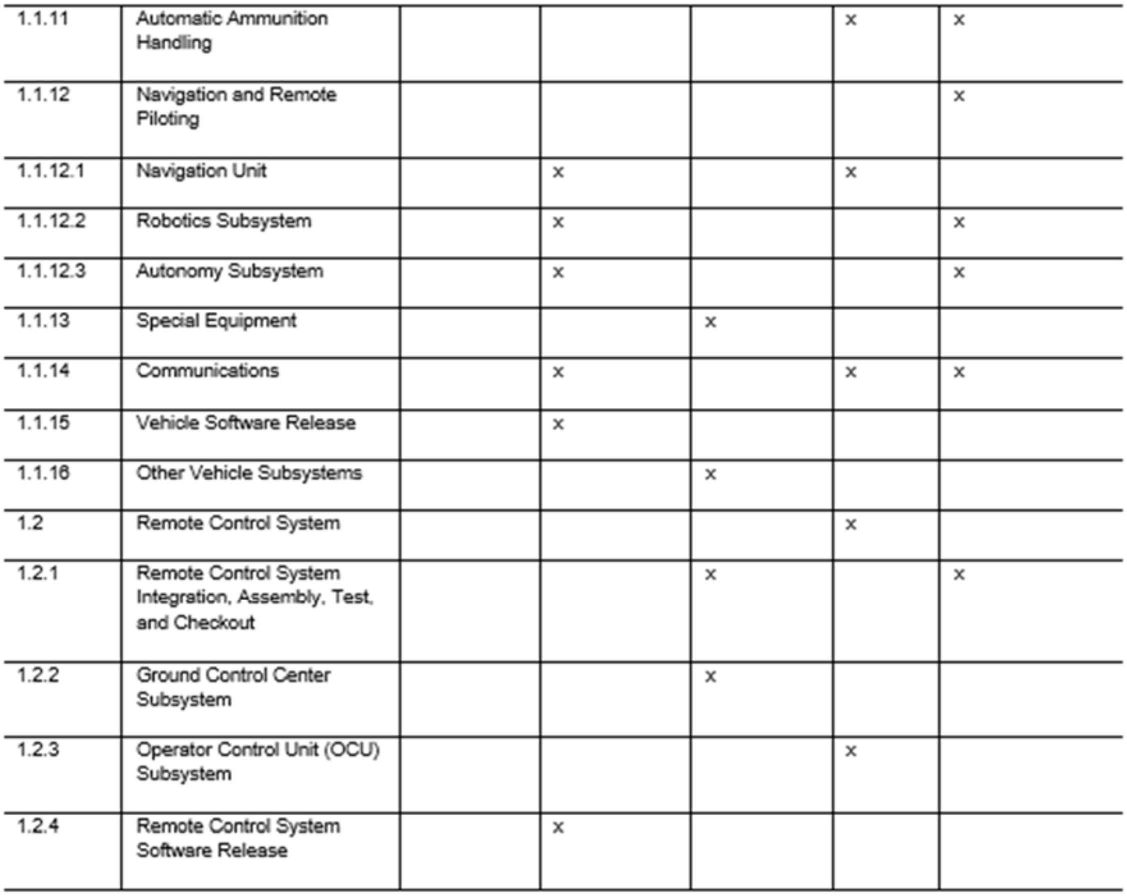
Figure 6. **Squad Mission Support System (SMSS™)**
(Lockheed Martin, n.d.)

As shown in Table 19, the five proposed cost models adequately capture all of the P-WBS elements of the SMSS™. In some cases, the cost of individual elements can be captured by more than one cost model. To ensure that costs are not double counted, the estimator should decide which of the cost models will be used for each WBS element. This decision could be based on the amount of fidelity provided by each cost model or the ability of the cost model to capture the WBS element's characteristics that influence cost.

Table 19. Types of Estimates Needed per Product Breakdown Structure Element

Type of Model Recommended

Ref. #	WBS Element (Mills, 2014)	Hardware (SEER-H)	Software (COCOMO II)	Systems Engineering (COSYSMO)	Weight-based CER	Performance-based CER
1	Squad Mission Support System (SMSS)	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
1.1	Common Mobility Platform Vehicle					x
1.1.1	Vehicle Integration, Assembly, Test, and Checkout			x		
1.1.2	Hull/Frame/Body/Cab				x	x
1.1.2.1	Main Chassis Structure	x			x	
1.1.2.1.1	Frame and Hull				x	x
1.1.2.1.2	Hood				x	
1.1.2.1.3	Deck Panels				x	
1.1.2.1.4	Skid Plate				x	
1.1.2.2	Electronics Box Structure				x	
1.1.2.3	Front Brush Guard				x	
1.1.2.4	Rear Brush Guard				x	
1.1.2.5	Front Sensor/Component Mount				x	x
1.1.2.6	Rear Sensor/Component Mount				x	x
1.1.2.7	Equipment Rack				x	
1.1.2.8	Pack Racks/Tail Gate				x	
1.1.3	System Survivability			x		x
1.1.4	Turret Assembly		x	x		x
1.1.5	Suspension/Steering					x
1.1.6	Vehicle Electronics		x	x		
1.1.7	Power Package/Drive Train	x				x
1.1.8	Auxiliary Automotive	x		x	x	x
1.1.9	Fire Control					x
1.1.10	Armament				x	x



1.1.11	Automatic Ammunition Handling				x	x
1.1.12	Navigation and Remote Piloting					x
1.1.12.1	Navigation Unit		x		x	
1.1.12.2	Robotics Subsystem		x			x
1.1.12.3	Autonomy Subsystem		x			x
1.1.13	Special Equipment			x		
1.1.14	Communications		x		x	x
1.1.15	Vehicle Software Release		x			
1.1.16	Other Vehicle Subsystems			x		
1.2	Remote Control System				x	
1.2.1	Remote Control System Integration, Assembly, Test, and Checkout			x		x
1.2.2	Ground Control Center Subsystem			x		
1.2.3	Operator Control Unit (OCU) Subsystem				x	
1.2.4	Remote Control System Software Release		x			

Once the appropriate cost models are determined for each WBS element, the cost can be calculated as the sum of the outputs of the five cost models, as shown in Equation 4.

$$\begin{aligned} &Cost\ (convert\ all\ individual\ outputs\ to\ \$K) \\ &\quad = (Hardware) + (COCOMO\ II) + (COSYSMO) \\ &\quad +(Weight\ Based\ CER) + (Perfomance\ Based\ CER) \end{aligned} \tag{4}$$

The expected unit cost would be in the range of $1 million to $100 million, depending on the capabilities and complexities of the UMAS. This is based on the historical results from the unit cost of the Global Hawk Unmanned Aircraft System ($92.87 million) and Modular Unmanned Scouting Craft Littoral ($700,000). If the estimated cost falls outside of this range, careful analysis should be done to ensure that the capabilities of the UMAS being estimated are truly beyond the scope of the historical data.

Another basis of comparison could be the two cost estimating relationships described in this section which consider flight hours and maximum takeoff weight. While these cost drivers would only be relevant for Unmanned Aerial Vehicles, they can serve as sanity checks when performance and weight are important considerations.

For the purposes of this section of the report, we are unable to provide a comparison of actual costs versus estimated costs to validate our proposed cost modeling approach. One reason is the proprietary nature of the data. Another is the lack of fidelity that is available to compare UMAS costs using the same cost elements, namely vehicle, ground control station, and support elements.

Additional Considerations for UMAS Cost Estimation

Test and Evaluation

Many systems engineering and project management experts advise concurrent planning of test and evaluation (T&E) during the earliest phases of a project (Blanchard & Fabrycky, 2003). In similar fashion, estimating the cost of these activities should also begin earlier rather than later. As budgets are allocated and costs are estimated, some key considerations on how the UMAS may be tested might be analytical testing, prototyping, production sampling, demonstration, and modification (Blanchard & Fabrycky, 2003). The current practice in many organizations is to focus most of the cost of product development and when the project reaches the T&E phases use the remaining funding. This often leads to reduced testing and schedule slippages.

2 Demonstration

Demonstration is one of the unique aspects of T&E because there are many categories or sub-sets of demonstrating a product's capability. The two that are most important are demonstrating systems integration and demonstrating full operational capability. The costs associated with these are very different, and will also vary by type of UMAS. Some questions to consider when estimating the UMAS, but specifically demonstrating the UMAS, are as follows:

Level of Autonomy:

a. At what level of autonomy is the UMAS designed to operate?
b. How will the level of autonomy influence safety, reliability, and integration to other systems?

Systems Integration:

a. Will these demonstrations coincide with the design reviews or be separate events?
b. What key system capabilities will your team want to demonstrate?
c. Will you focus only on risky technology or demonstrate solutions to previously developed concepts?

Full Operational Capability:

a. Who is your audience? Depending on whether it is government or commercial this will play a huge factor in where and how you demonstrate.
b. Will you need to create an operational scenario to show how the UMAS integrates into the current paradigm of its intended field? For example, will you need to have a mock battle, or create a queuing backlog at a distribution plant or border crossing?

Conclusion

In this section, we described unique considerations of Unmanned Autonomous Systems. In particular, life cycle models that help structure cost estimates, existing cost estimation methods, product work breakdown structures, and parametric models. These led to a case study that described an Army Unmanned Vehicle and a recommended approach for estimating the per unit life cycle cost. We concluded by discussing two unique considerations of estimating the cost of the UMAS—levels of autonomy, test and evaluation, and demonstration—that have the potential to significantly influence the complexities involved with transitioning a UMAS into operation.

As the UMAS continue to be developed and deployed into operation we anticipate the maturity and accuracy of estimating their costs will similarly increase. At the moment, reliance on complete work breakdown structures, comparisons with historical data, and utilization of existing parametric cost models can provide a reliable estimation process that can be used to develop realistic cost targets.

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