DEVELOPMENT OF A METHODOLOGY TO OPTIMALLY SELECT SUBSYSTEMS FOR SUBSEQUENT INTEGRATION INTO HELICOPTER SYSTEMS

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ABSTRACT

A systems engineering methodology and model are presented for selecting subsystems and interfaces that meet technical and budgetary requirements, with specific emphasis on helicopter development. The methodology expresses the problem of subsystem selection in terms of a graph theoretic model, conditioned for optimization based on enterprise goals. The model is visually represented as a network flow where nodes represent subsystems, and arcs represent subsystem interfaces. The interface parameters consist not of physical and functional relationships, but instead represent cost, schedule, technical performance, and risk. Those key technical and budgetary attributes are drawn into the model as optimization objectives. Mathematical formulation describes the complex system objectives, constraints, variables, and dependencies in terms of a multi-objective optimization model where parameters important to the product integration scheme are simultaneously quantified as part of the system model. The solution set is a Pareto optimal list of alternative subsystems ranked in order of preference, allowing the developer a selection of subsystem combinations to meet technical performance requirements and satisfy budgetary goals.

INTRODUCTION

Several sources of complexities are encountered during the integration of subsystems into complex systems. These sources include (a) convolution and perhaps ambiguousness of the system's functional requirements, (b) availability of numerous alternative subsystems that can be used to meet these requirements, and (c) limitations from all considered technological and budgetary (monetary and schedule) constraints. For instance, complex systems are required to function in a variety of operational and environmental modes. Such multi-mode/multi-environment operation results in conflicting functional requirements that complicate the integration process of these systems. In addition, each of the specified requirements can be satisfied through numerous alternative subsystems differing in their basic and interface costs, compatibility, performance, integration duration, risk to integrate, etc.

The subsystem selection process increases in complexity as the number of alternative subsystems increases, requiring more analysis to capture tradeoffs among the different possible designs. As a result, the integration processes that occur between the fundamental phases of system engineering are subjected to conflicting forces from several technological and/or budgetary constraints. For instance, an integrated system has to demonstrate certain performance levels while minimizing risk and meeting cost and schedule constraints. The problem is magnified on air vehicles, and even more so on vertical lift aircraft. Given the multi-objective nature of modern helicopters, both commercial and military, they can be categorized as complex systems.

The process of systems engineering requires an iterative approach to system design, generation of alternatives, tradeoff analysis, and integration. Systems integration processes and tools (e.g., requirements management, risk management, and performance analysis) assist in capturing and managing the integral relationships between the elements of a system. Requirements definition and analysis tools are used to characterize the integrated system and validate customer requirements. Functional analysis and allocation tools assist with decomposition of the system into subsystem components, to provide a work breakdown for estimating cost and schedule of the engineering effort. Design synthesis tools help assess the integrated performance, risk, and cost of the integrated system. System analysis and control tools help balance all aspects of the systems engineering process to keep product and process development on track. These tools

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are valuable to the systems engineer and provide an important service to the process of integrating a system.

The process of systems engineering, and specifically the selection of subsystems, utilizes a wide range of processes and models (e.g., performance, risk, collaboration, and earned value) to minimize the problem set into manageable entities. Available systems engineering toolsets (Ref. 1) decompose tasks associated with subsystem selection and provide information that allows the systems engineer to perform trade studies, leading to optimal system architectures through systems engineering feedback loops. Systems engineering process relationships illustrated in Fig. 1 encompass the fundamental systems engineering process (Ref. 2), the SIMILAR process (State, Investigate, Model, Integrate, Launch, Assess and Re-evaluate) introduced by Bahill and Gissing (Ref. 3), and a decomposed version of the Systems Engineering Vee model first published by Kevin Forsberg and Harold Mooz (Ref. 4). Design synthesis and alternative investigation are principal steps in each system engineering process.

Significant opportunity for project cost avoidance, risk reduction, and identification of preferred alternatives is available in the early phases of the systems engineering process. Mistakes made early in the system life cycle can have substantial negative impacts on the cost of the system. Buede (Ref. 5) presents a comparison of *cost commitment* versus *cost incursion* to illustrate the importance of decision-making during preliminary and detailed design phases of system development. At the completion of the detailed design and integration of a typical system (Fig. 2), 80% of the system development costs are committed, while only 20% of the costs are incurred. Therefore, 60% of the total development cost is at risk to overrun prior to constructing the system.

The task of system integration is inherently difficult due to its multi-objective nature. The system developer converts requirements into a performance-based product while accounting for programmatic concerns of risk, schedule, and cost. The common thread to simplifying this difficult task is to model the system with software tools early in the development process. Models allow the systems developer to capture multiple attributes and dependencies of the system and manipulate them into an organized solution (Ref. 6). However, the difficulty is somewhat compounded by the array of available models, each solving part of the problem, but none solving the whole. One must take the output from the models and use the data to perform additional tradeoff analyses, and then manually integrate the data to find alternative optimal solutions. A methodology and associated model specific to automating the tradeoff analyses of subsystem selection can assist the designer in this regard.

Optimal system design synthesis can be formulated through adopting a graph theoretic multi-objective approach, conditioned for optimization based on several enterprise and

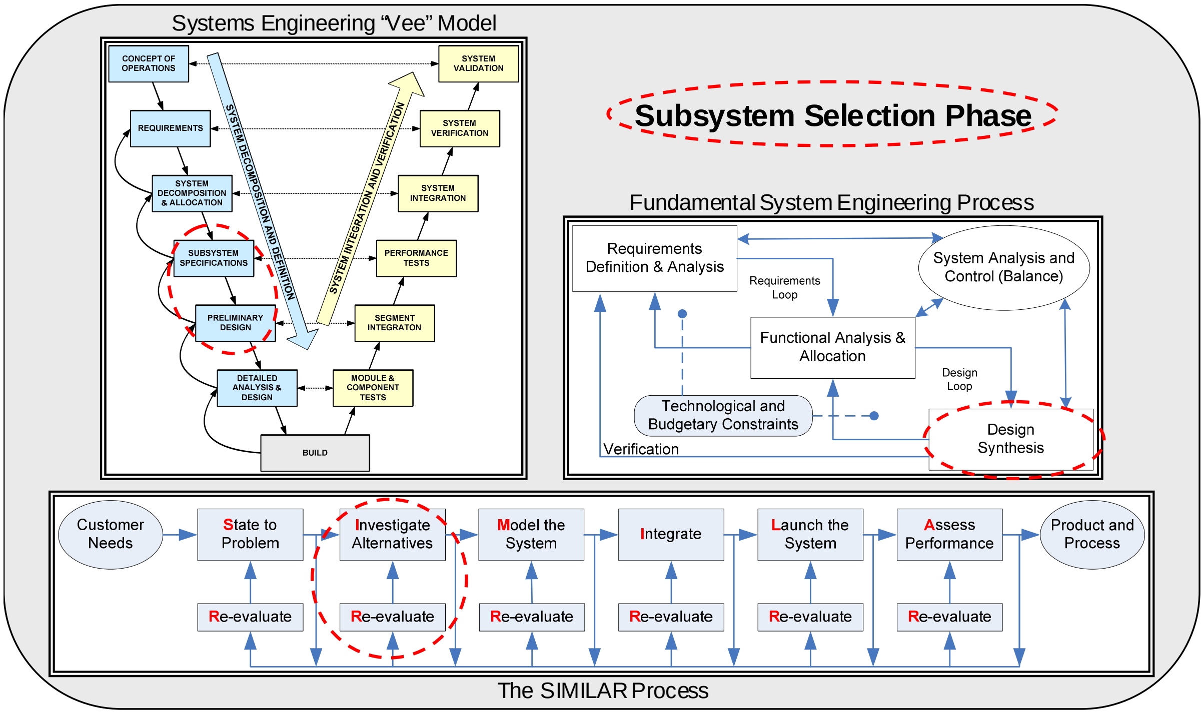

Fig. 1. Subsystem selection within systems engineering processes.

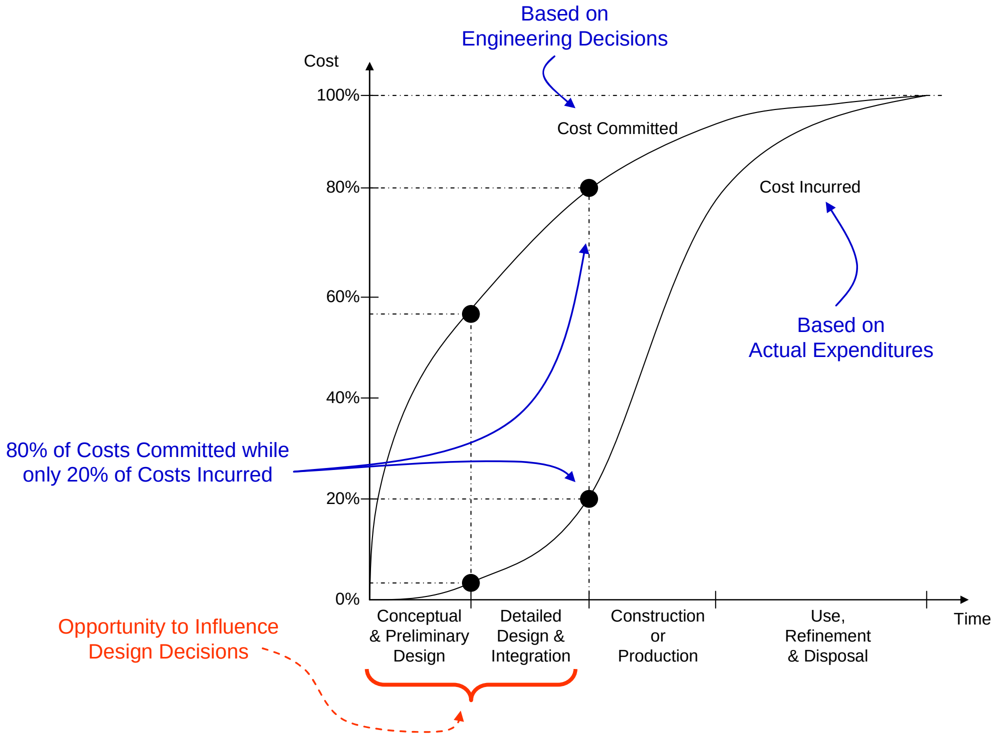

Fig. 2. Cost commitment and incursion in the system life cycle (Buede, 2000).

design goals. In graph theory, a network flow model is formulated where nodes represent subsystems, and interconnecting arcs represent subsystem interfaces. The interface parameters consist not of physical and functional relationships among the subsystems, but instead represent the multi-objective parameters of cost, schedule, technical performance, and risk. Cost is defined as a monetary expenditure for hardware, software, equipment, facilities, etc. Schedule is defined as the time to acquire the subsystem or component, and perhaps the design time to integrate it into the system. Performance is defined as the technical parameters applicable to system requirements, possibly tracked as a figure of merit or technical performance measure. Risk is defined as the intrinsic likelihood and consequence associated with the balance or imbalance of cost, schedule, and technical performance. The conceptual modeling framework within the systems engineering process is illustrated in Fig. 3. The focus of the systems engineering process within this model extends from subsystem specification through design synthesis.

A wide array of problems found in multiple industries is represented as network flows. Complex system designs are characterized as networks (graphs). The system hierarchy can be represented as a network flow. A graph theoretic approach to solve helicopter system development problems

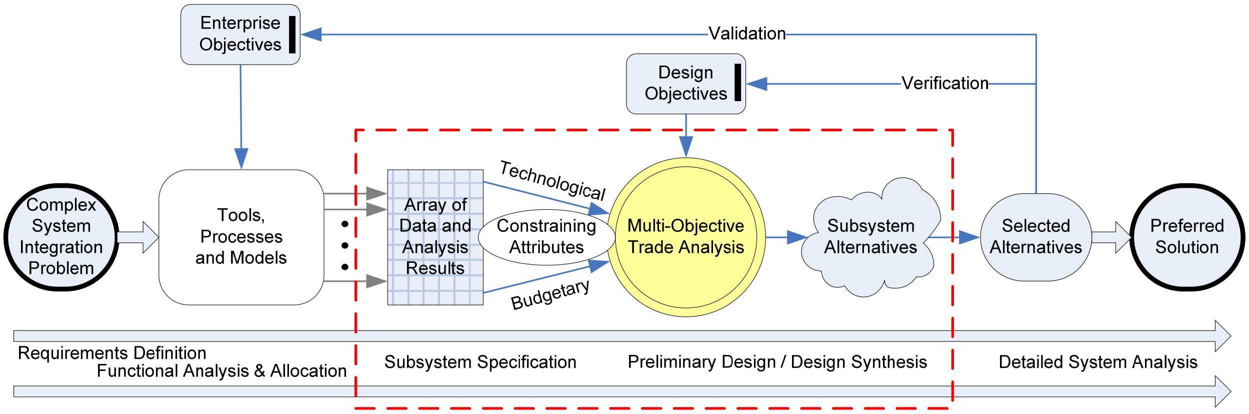

Fig. 3. Conceptual model for optimal design synthesis.

calls upon the network flow problem domain described by Ahuja (Ref. 7). The framework input is the technological and budgetary constraints associated with alternative subsystems. The collection of subsystems partially or fully satisfies the system's predefined requirements allocated from the initial top-down development.

System engineering tools and models are applied to the helicopter system integration problem. Enterprise objectives are identified and form the basis from which system constraints are developed. The problem is decomposed into parametric data and analysis results at the subsystem level, using available system engineering tools, models, and product data sources. The resulting data is organized into an array of technological and budgetary attributes (subsystem specifications) for entry into a multi-objective trade analysis model. The collection of subsystems partially or fully satisfies the system's predefined requirements allocated from the initial top-down development. The flow of product information and analysis results to the graph theoretic model is illustrated in Fig. 4.

Technological constraining attributes are generated by systems integration tools capable of supporting trade studies, system decomposition, job sequencing, resource allocation, and interfaces (physical, software, and organizational). Budgetary constraints comprise representative attributes for estimation of effort (design cost and schedule), performance measures, integrated risk level values, and fixed costs associated with integration fixtures and capital equipment. Historical data supplements the budgetary constraints with empirical values and lessons learned from previously executed projects.

Given the multi-objective nature of the problem, a multi-objective trade study determines a set of feasible design paths. The multi-objective model takes the constraining subsystem specifications and applies them to design objectives. As subsystem alternatives are developed, the results are synthesized to a set of alternative design schemes. The preferred solution is selected through detailed system analysis. The resulting set of design alternatives is verified to meet design requirements and validated to meet enterprise objectives. The selected schemes comprise a preferred balance of cost, schedule, performance, and risk. Exiting the model, the system engineering process continues with design construction, subsystem test and integration, system level test and integration, then system verification and validation. The overall modeling framework is illustrated in Fig. 5.

Given the system requirements, the process starts with a system architecture where functional requirements are analyzed and allocated to subsystem specifications. A collection of subsystems that satisfies the specifications is identified and their characteristics collected into an array of relevant parameters. Each subsystem is defined in terms of its budgetary and technical interface parameters. One or more subsystems that satisfy any of the system functions and parametric requirements are included in the array and identified as alternatives through design synthesis. The overall hierarchal representation of the system design is then used to provide sequencing of the required subsystem identification and alternative analysis processes. Using this hierarchal structure, the modeling framework develops a graph representation of the system such that a path in this graph represents a feasible scheme. Systems analysis arranges design alternatives in order of highest to lowest

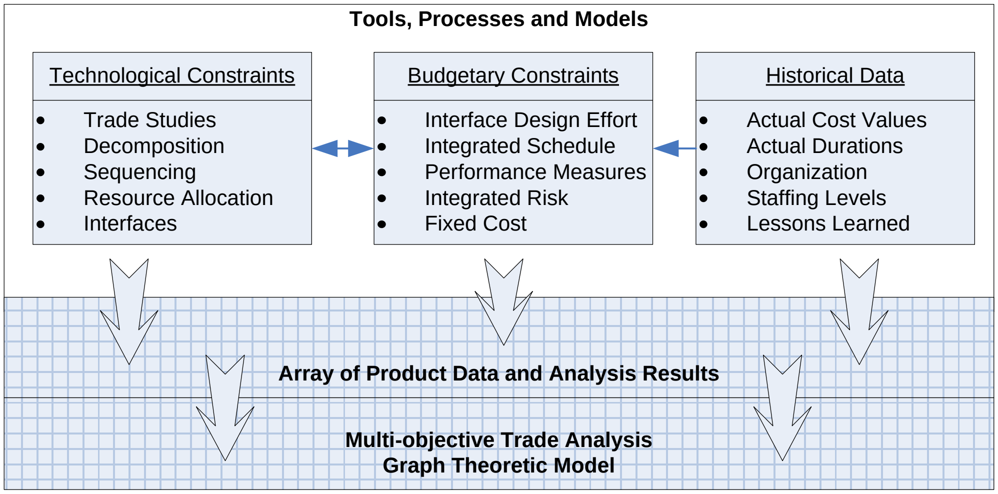

Fig. 4. Product data and analysis results feed the graph theoretic modeling framework.

priority, representing the Pareto optimal list of schemes for the system.

MILITARY HELICOPTER DEVELOPMENT FROM A COMMERCIAL PLATFORM

The system design and development (SDD) phase of a military helicopter program is to design, build, test, and qualify SDD aircraft to precede low-rate initial production (LRIP), leading to full-rate production (FRP). The basis for a commercial off-the-shelf (COTS) contract is to develop and field aircraft at a rapid pace from contract award to first unit equipped (FUE). Fast track programs to replace aging fielded aircraft call for new designs to implement a combination of COTS and military off-the-shelf (MOTS) subsystems. This approach is intended to minimize new product development to meet a constrained schedule. The goal is to select components requiring no additional airworthiness qualification beyond that originally accomplished for commercial airworthiness certification. However, additional analysis and testing may be needed to substantiate airworthiness.

A fast-track COTS helicopter program may require first flight to be accomplished prior to CDR, whereas the normal sequence of events places first flight after CDR. The reversal of these two events adds cost and schedule risk to the program by allowing the aircraft to be built and tested prior to the design being complete. A combination of short development time and significant application of COTS components places airworthiness qualification at high risk to the development program. Subsystem components should be selected so that functional capability achieves required technical performance. Technical risk is monitored due to unknowns affecting potential redesign.

COTS-Based System Acquisition for Military Use

A commercial off the shelf (COTS) item is one that is

- sold, leased, or licensed to the general public;
- offered by a vendor trying to profit from it;
- supported and evolved by the vendor who retains the intellectual property rights;
- available in multiple, identical copies; and
- used without modification of the internals (Ref. 8).

A COTS approach to a new Department of Defense (DoD) helicopter program is viewed from two perspectives; 1) COTS is in accordance with DoD directives, instructions, handbooks, and regulations; and 2) COTS is developed in accordance with commercial best practices. Two approaches to subsystem component acquisition and qualification of a new helicopter are expanded from the perspective of DoD and industry.

The U.S. DoD recognizes that existing COTS functionality and solutions drawn from a diversified range of large and small businesses shall be considered (Ref. 9). For example, the Army Airworthiness Qualification requirements for U.S. Army Aircraft Systems (Ref. 10) recognize that adoption of COTS equipment for government aviation use is a viable approach. When COTS is selected, AR 70-62 states the equipment will include an airworthiness assessment. Based on the assessed airworthiness impact, appropriate airworthiness documents will be required for installation and operation of the COTS equipment. AR 70-62 also states that

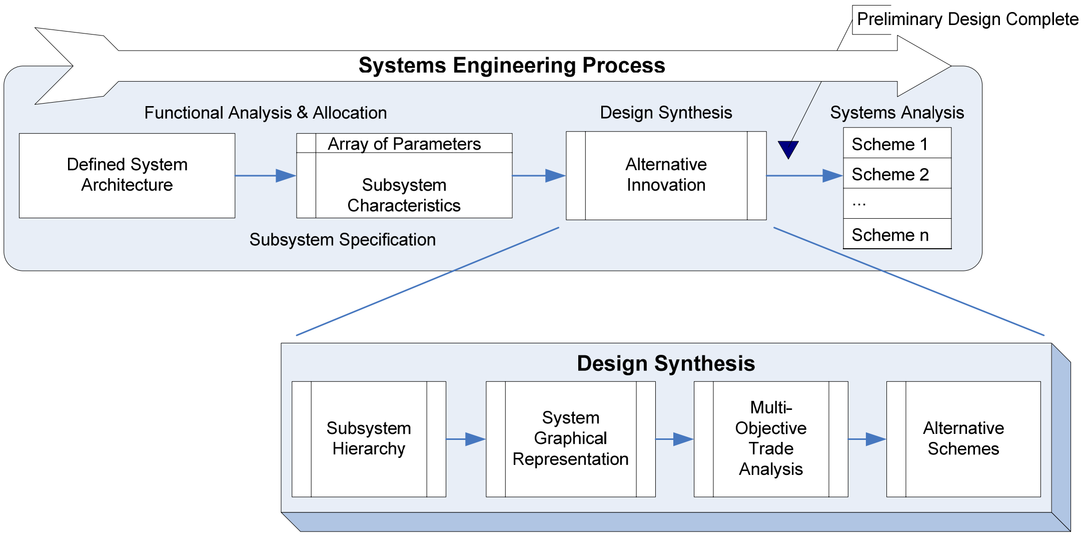

Fig. 5. Overall modeling framework with emphasis on design synthesis.

commercial off-the-shelf equipment adopted for government aviation use will be assessed for airworthiness impact. The assessment includes:

1. Review of any existing airworthiness approval for potential adoption if applicable to the Government system (i.e. Technical Standard Order [TSO]), and

2. Determination of the airworthiness qualification impact of the COTS equipment and its installation on the authorized configuration.

The DoD Defense Acquisition Guide (2004) (Ref. 11) recognizes the use of commercial items that offer significant opportunities for reduced development time**,** faster insertion of new technology, and lower life cycle costs, owing to a more robust industrial base. Maximum use of mature technology provides the greatest opportunity to hold fast to program cost, schedule, and performance requirements, and is consistent with an evolutionary acquisition strategy. However, the Defense Acquisition Guide cautions that no matter how much of a system is provided by commercial items, the program manager should still engineer, develop, integrate, test, evaluate, deliver, sustain, and manage the overall system. Particular attention should be paid to the intended usage environment and understanding the extent to which this differs from (or is similar to) the commercial usage environment; subtle differences in usage can have significant impact on system safety, reliability, and durability. In other words, COTS items should be selected to meet the overall system requirements.

An approach to developing a helicopter for rapid fielding in a military environment is to derive it from an FAA-certified commercial helicopter. The aircraft can be modified to execute military missions while maximizing the use of commercial flight-qualified components. The helicopter development program can be modeled to exploit the availability of COTS equipment. The airframe and mechanical systems can use a significant number of heritage commercial components previously qualified to FAA standards. For example, many key elements of a helicopter can be incorporated into the military platform: propulsion, rotors, drive, and basic airframe. Major changes are required in the area of wiring and avionics, or mission equipment package (MEP), which in turn drive changes to interfacing airframe components. The avionics system comprises the largest unknown qualification basis. A fishbone illustration of the MEP design basis is shown in Fig. 6.

A commercial helicopter model is developed into the military platform by replacing standard commercial subsystems (hardware and software) with those qualified for military use. In addition, mission-specific systems are added to satisfy the military requirements. The component selection criteria and resulting procurement of those components follow the guidance of requirements established in an airworthiness qualification specification (AQS). The COTS approach to component selection and qualification needs to follow a combination of DoD documented guidance and commercial best practices to ensure compliant airworthiness, while minimizing time to fielding. DoD literature summarizes that COTS does not translate to "as-is." COTS items should be selected to meet overall system requirements, which include functional, performance, environmental, and electromagnetic requirements. Airworthiness qualification of COTS components must be substantiated with existing qualification report data or results from additional tests. The "best value" approach to

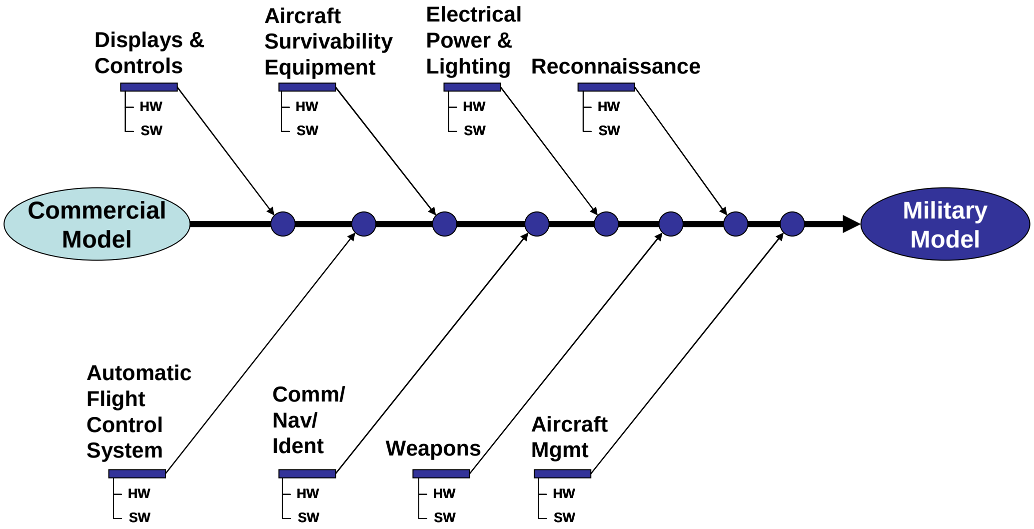

Fig. 6. Mission equipment design basis.

acquiring COTS components to meet all requirements is to perform system level testing in areas where there is a shortfall in component level qualification data. The end goal is to provide sufficient qualification basis to prove the components are airworthy. However, the airworthiness qualification of the aircraft is from two aspects: the system level and the component level. The additional requirement for component level qualification drives risk into the program, since the basic helicopter architecture is already designed. By introducing subsystem components to the rigors of substantiation and/or qualification to military environmental and electromagnetic standards, there is potential for failure that could require redesign or selection of different components, thus increasing risk to cost and schedule.

A phased approach to qualify all subsystem components either by similarity analysis or test could entail redesign of existing components or selecting new components. Given the large number of components for which airworthiness and environmental qualification must be substantiated, a component qualification matrix (CQM) is developed to capture the multi-objective elements (cost, schedule, performance, and risk) affecting the cost of design and integration. The monetary cost elements include test facility, test execution, support equipment, test assets (units under test), engineering analysis, and technical reporting. The schedule objective is to provide aircraft to the field with minimal or no flight restrictions levied on it. Satisfactory completion of qualification for all components prior to releasing the fleet to the field will result in minimal flight restrictions. The performance elements include Environmental Engineering Standards and Laboratory Tests (Ref. 12) and Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment (Ref. 13). The risk elements are biased toward cost and schedule: cost to test, and the potential for component redesign cost based on the test outcomes; and schedule to field the helicopters as soon as possible. Technical risks are centered on mechanical, electrical, and software interfaces likely to change from the original design to satisfy the functional and environmental requirements.

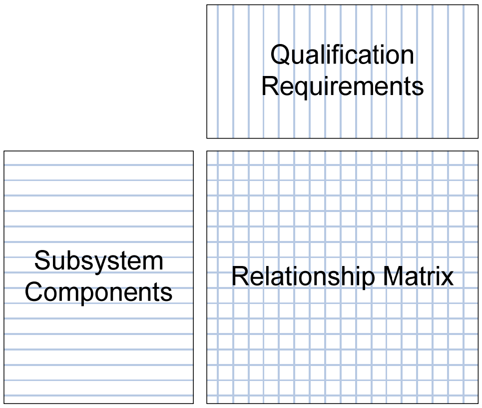

Fig. 7. Subsystem qualification matrix layout.

COTS Helicopter Systems Qualification for Military Application

A component qualification method is proposed to achieve a COTS solution to developing the mission equipment package for a military helicopter. The mission equipment subsystem components are selected based on mission requirements and certification status. The objective for substantiating component qualification is to acquire documentation from previously accomplished qualification tests to validate the qualification requirements. From the acquired documentation, the qualification basis (by similarity, by analysis) is then established. Where documentation is not available, testing is needed to establish a basis for an airworthiness release (AWR). In summary, the component selection criteria for integration are as follows:

- functional capability to meet system requirements
- previously certified/qualified
- prior integration with the common military avionics architecture
- physical properties (size, weight, electrical, interface)
- cost (procurable/sustainable/business case)
- availability (lead time/obsolescence threat)
- environmental requirements (operation on existing commercial and/or military platforms — rotary wing, fixed wing)
- risk to design change or additional tests based on subsystem dependencies

The systems qualification scheme is based on predefined common avionics architecture, a commercial model airframe and mechanical systems, common non-developmental components to satisfy the required functions, and a commercially developed propulsion system. Interfacing hardware and software are tailored to the COTS components. However, interfacing COTS components to operate as a system is typically a much larger engineering task than anticipated. A report on lessons learned from commercial item acquisition for DoD programs (Ref. 8), finds that modifying commercial items to bridge the gap to the DoD system requirement can cause significant cost and schedule overruns. Modifying system performance requirements to align with the COTS acquisition strategy can translate to cost and schedule savings.

Subsystems, software, and their alternatives are selected to satisfy system level and component level functional requirements. At the component level, an environmental performance requirements spreadsheet is developed and arranged similar to Fig. 7, which lists the subsystem components on the left column, and the environmental qualification requirements on the top row; the relationship matrix indicates the type of qualification to be completed (test, similarity, analysis, or not applicable).

The CQM can also be characterized as a static design structure matrix (DSM), where subsystem component dependencies can be modeled. However, the CQM is more in line with the correlation matrix found in quality function deployment (QFD), where subsystem dependencies can be measured (commonly referred to as "the House of Quality"). The DSM was originally conceived by Donald V. Steward in 1967 as a model to evaluate cause and effect associated with engineering a complex system (Ref. 14). Application of the DSM continued to be expanded to address the problem of complex system decomposition and integration (Refs. 15, 16, and 17). Quality function deployment (QFD) integrates program planning and flowdown. QFD originated in the 1960s at the Mitsubishi Kobe shipyards in Japan, aimed at delivering products and services that efficiently satisfy customers (Ref. 18).

Subsystem Selection Methodology

The subsystem selection methodology is constructed from four primary components. Elements of the subsystem selection methodology are the following:

- source of alternative subsystems
- array of parameters
- multi-objective model
- Pareto list of optimal sets of subsystem alternatives

The source of alternative subsystems is through a supply chain network stemming from industrial manufacturers. Subsystems can be purchased "off-the-shelf" (OTS), meaning they can be selected and purchased from a catalog, or subsystems can be built to order as new development. OTS items are selected to meet system requirements; however, it is rare for an OTS subsystem to meet all system requirements. Therefore, OTS subsystems are selected based on multiple criteria such as availability, cost, performance, compatibility with other subsystems, etc. Newly developed subsystems are built to meet system requirements as partitioned to the subsystem specification design documents (SSDD) and flowed to the manufacturer via a statement of work (SOW). The SSDD and SOW are flowed to capable manufacturers with a request to quote a price and delivery schedule. The price and delivery schedule, plus the performance parameters, are inputs to the parameter array. The supply chain flow is illustrated in Fig. 8.

Available subsystems that satisfy or nearly satisfy system requirements are tabulated along with their associated components. For adequate resolution to the subsystem selection process, components that comprise the subsystem are cataloged with their technical and budgetary parameters. The association of components to subsystems for testing this element of the methodology is illustrated in Fig. 9. This level of detail is tested to determine if cataloging at the component level is sufficient, or if a lower level is necessary.

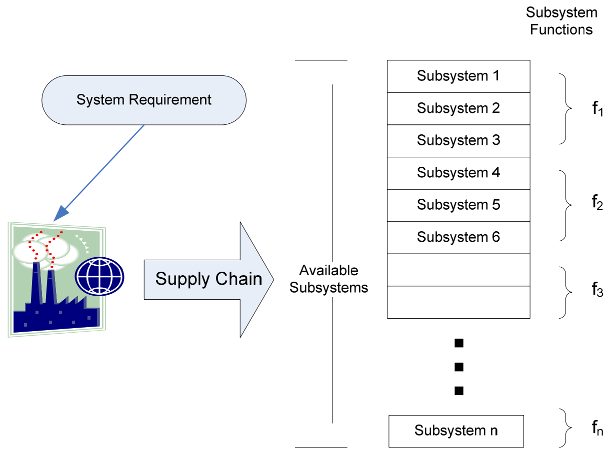

Fig. 8. Source of available subsystems.

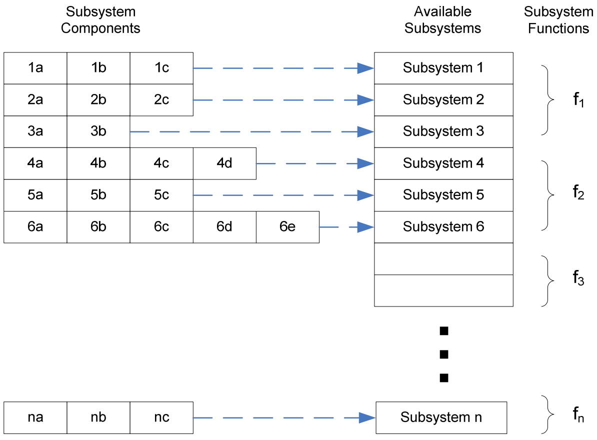

Fig. 9. Subsystem component structure.

For example, assume a choice between three subsystems (s1, s2, s3) to perform a function. Only one subsystem can be chosen. The hypothetical subsystem can be described as a navigation system or communication system on an aircraft or ship, comprised of a set of components such as radios and antennas: (1a, 1b, 1c) for subsystem s1, (2a, 2b, 2c) for subsystem s2, and (3a, 3b) for subsystem s3. Objective parameters include cost, schedule, reliability, and risk to integrate (i.e., compatibility). Technical and budgetary requirements are formed into an array of subsystem specifications and budgetary values. The left side of the array is a list of available subsystems considered for inclusion into the higher level system. The top row of the array contains technical specifications and budgetary values of cost and schedule. The intersection of the left column and top row is the parameter value. The format of the structured array is illustrated in Fig. 10.

Structured parameter arrays can be described as a design structure matrix, "House of Quality" using QFD, or casual engineering spreadsheet. In this case, the array takes the form of a relationship matrix in a "House of Quality" where the left column is the "What" and the top row is the "How." The structured parameter array is the collection point for data provided to the multi-objective model. The multi-objective model serves as the central ingredient for the systematic trade analysis.

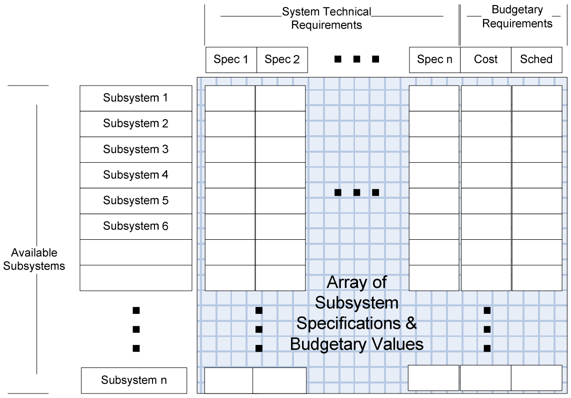

Fig. 10. Structured array of subsystem specifications and requirements.

Pareto optimal lists are the product of the multi-objective model output file. Structured lists are priority-ranked based on design objectives. For example, priority ranking of design objectives might be cost, schedule, performance, and risk. But the ranking could also be arranged with the opposite priority, or any other combination of objectives. In addition, the result can be concurrently ranked to multiple design objectives. The structure of the Pareto optimal lists is illustrated on the right side of Fig. 11.

Hypothetical Integration Problem Applying the Graph Theoretic Model

A hypothetical case is introduced as a generalized method to apply the graph theoretic approach to a simple subsystem selection problem. To help visualize the application of this approach, a real world integration problem is introduced. Let system "*a*" represent a data communication system that

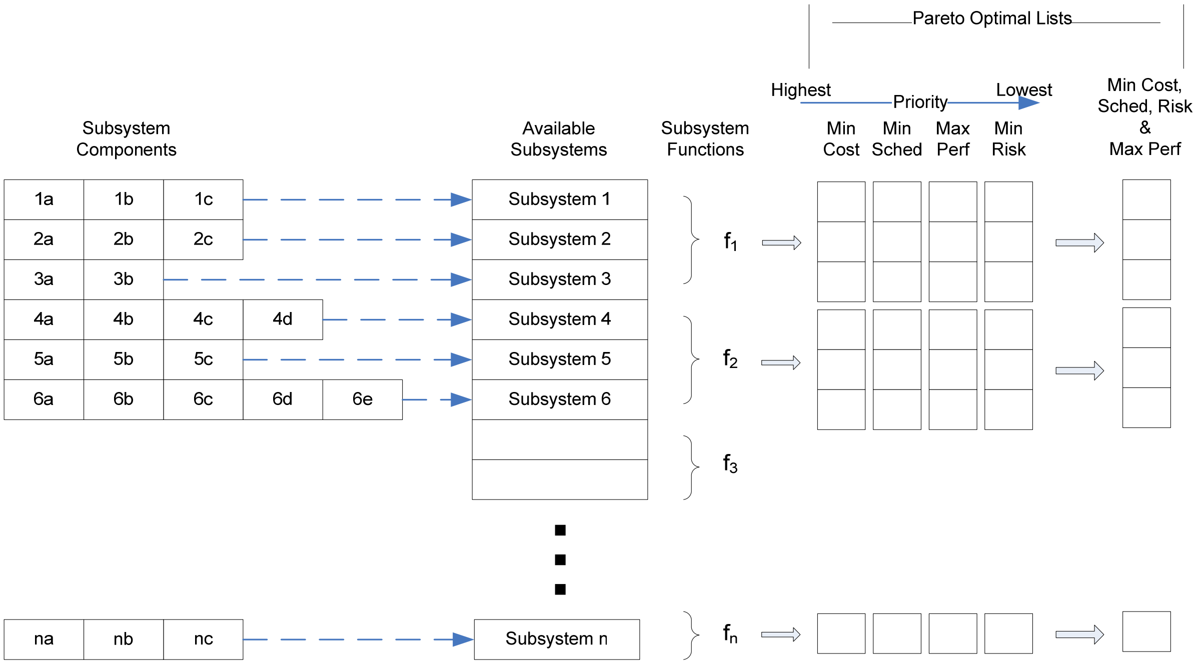

Fig. 11. Structured Pareto optimal lists.

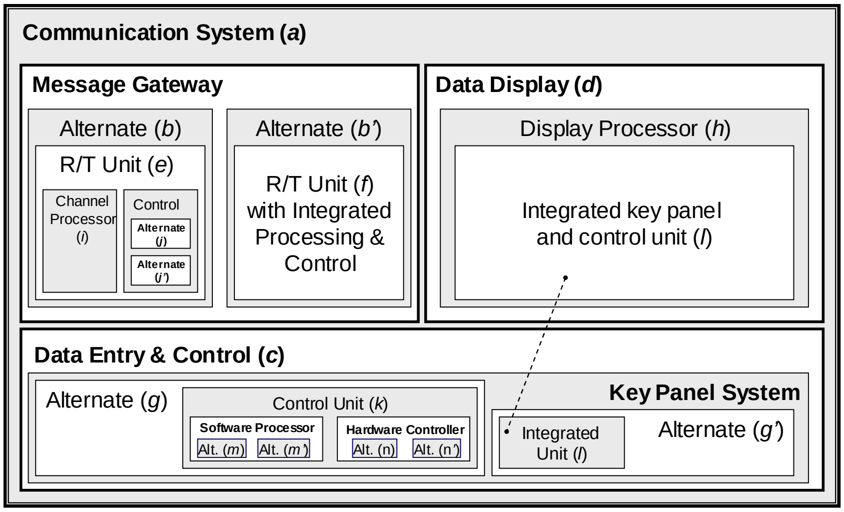

Fig. 12. Hypothetical communication system architecture.

provides a gateway to a data communication network, which allows the host platform to participate. Subsystems “*b*” through “*n*” represent component candidates of the data communication system to be integrated onto the host platform to allow it to participate on net-centric channels. The objective is to select one or the other based on optimality. The architecture of the hypothetical data communication system is shown in Fig. 12.

A simple representation of this system examines attributes associated with cost and duration data. Again, these attributes are simplified to demonstrate the modeling approach without the distraction of complicated numbers. For purposes of example, assume the attributes for each arc are values collected from subsystem data sheets and casual cost and schedule estimating tools. Cost and duration attributes (μ_{ij}^m, μ_{ij}^d) are assigned to arcs as interface cost μ_{ij}^m between the lower and higher-level subsystems, and subsystem upper-level acquisition duration μ_{ij}^d. Cost and duration attributes (β_i^m, β_i^d) are assigned to nodes that represent basic subsystem costs. The subsystem acquisition price is represented by β_i^m, while β_i^d represents acquisition duration for logistics, transportation, storage, transition time, etc. For illustration purposes, the values assigned to cost attributes are normalized units representing cost and duration. Hierarchal structure “a” is provided as an example and illustrated in Fig. 13.

A subsystem node with the same fill shade and style of an adjacent node are alternate candidates for inclusion into the system. Nodes with bold borders are incompatible and both cannot be included in the final set of subsystems. The nodes represent different subsystems considered for system “a”. Arcs represent possible budgetary interfaces between the different subsystems. Two cost attributes are considered in this example, namely subsystem cost and the duration of its acquisition. For a basic subsystem, the monetary cost and duration required for its acquisition are considered. Cost and duration attributes are simplified to allow clear explanation of the approach. All shared components are assumed to be hardware. Thus, they are reproduced for each higher-level sharing system.

The hierarchal structure is converted into a directed acyclic graph (DAG) and the cost attributes for each arc in this DAG are cataloged in the structured data array. In graph theory, a DAG is defined as a data structure having ordered arcs and

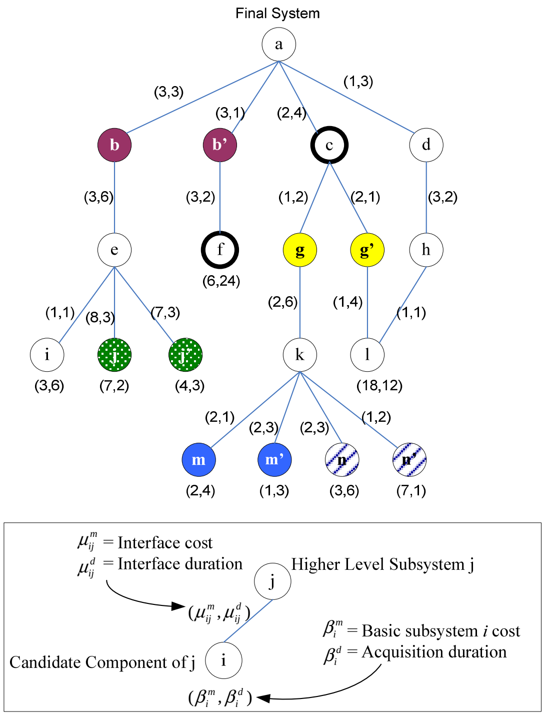

Fig. 13. Hypothetical system hierarchal structure.

no path returning to the same node (i.e., no cycles). Any route is one integration scheme. Therefore, the integrated system DAG represents all possible paths to a final system solution. Given the multi-objective nature of the subsystem selection problem, a multi-objective shortest path (MOSP) algorithm is used to provide a set of non-dominated paths in this graph. A path is defined to be non-dominated if this path outperforms all other paths in at least one of the considered objectives (Ref. 19). These paths represent the Pareto optimal integration alternatives for the system. Labels associated with these paths define the cost, schedule, performance, and risk of the alternative subsystem sets. The MOSP retrieves input parameters from the structured parameter array and the directed acyclic graph. The array provides budgetary constraints and the DAG provides interface constraints. A set of non-dominated alternative design schemes is output from the MOSP algorithm, providing input to system analysis where the optimal scheme is selected. The corresponding DAG with defined arcs is illustrated in Fig. 14, representing the set of non-dominated paths that are generated from the origin node to every branching node in the graph.

For instance, at node *i*, two non-dominated subpaths are generated. The first subpath implies that component *j* is used with acquisition cost and duration of fifteen and five units, respectively. The second subpath implies that component *j*' is used with a total acquisition cost and duration of eleven and six units, respectively. Clearly, neither of these two alternatives fully dominates the other. Component *j*' has less cost than the cost of component *j*. However, component *j* dominates in terms of acquisition duration. Similarly, the algorithm generates seven non-dominated integration options at node *c*.

Allowing the algorithm to proceed until the final destination produces all possible subsystem sets for this system. The system has seven possible non-dominated design options illustrated in Fig. 14. Four of these seven design options (options 1, 4, 5 and 7) must be eliminated, as they include the two incompatible subsystems *c* and *f*. The remaining subsystem sets to be considered are options 2, 3 and 6. Option 3 in Fig. 15 shows the hierarchal structure of the fastest-to-develop option, and option 6 in Fig. 16 shows the hierarchal structure of the least cost design option.

Design option 3 (fastest), which includes components *b*, *e*, *i*, *j*, *n*', *m*, *k*, *g*, *c*, *l*, *h*, and *d*, yields a cost of 65 units and duration of 59 units. Design option 6 (least cost) includes components *b*, *f*, *b*, *e*, *i*, *j*', *n*', *m*'', *k*, *g*, *c*, *l*, *h*, and *d* with cost and duration of 60 and 61 units, respectively. Speeding up the development process comes with more expenses in this case.

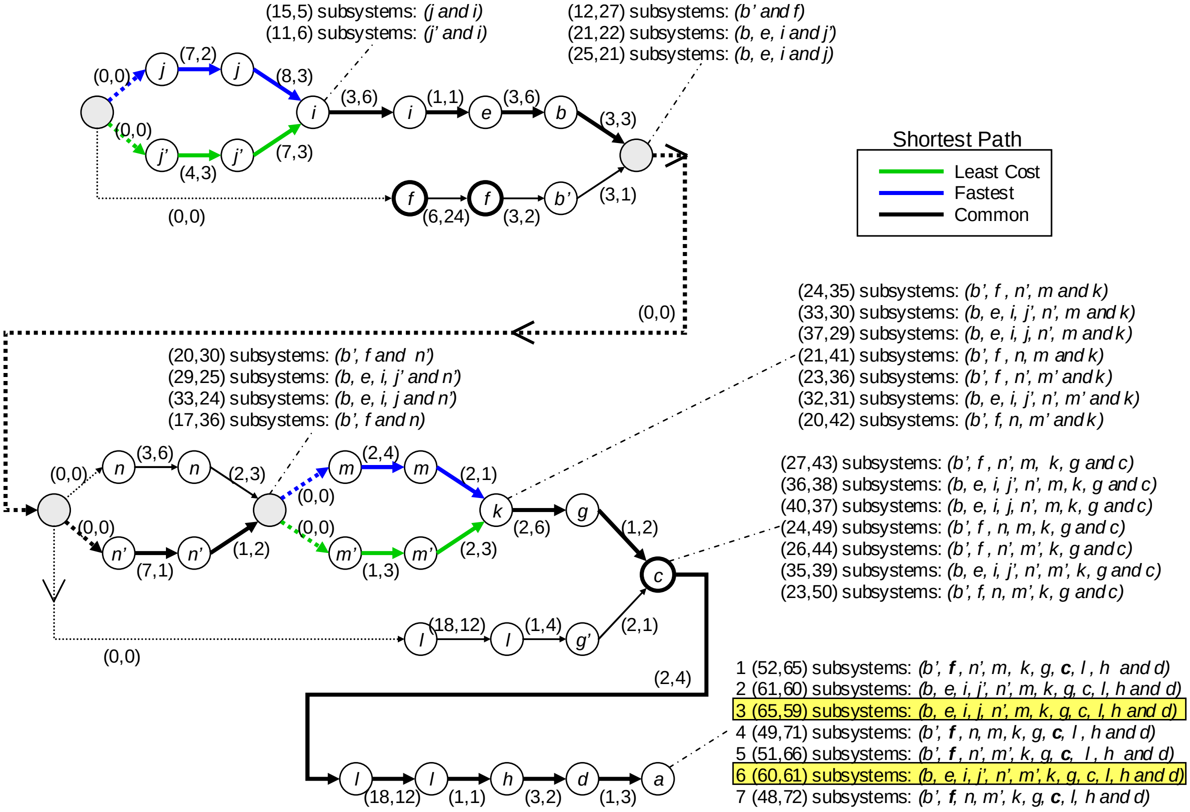

Fig. 14. Application of MOSP algorithm.

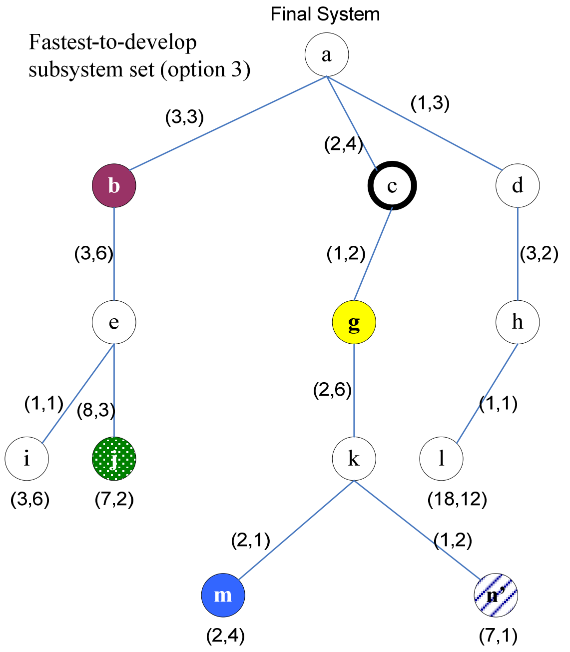

Fig. 15. Fastest-to-develop subsystem set.

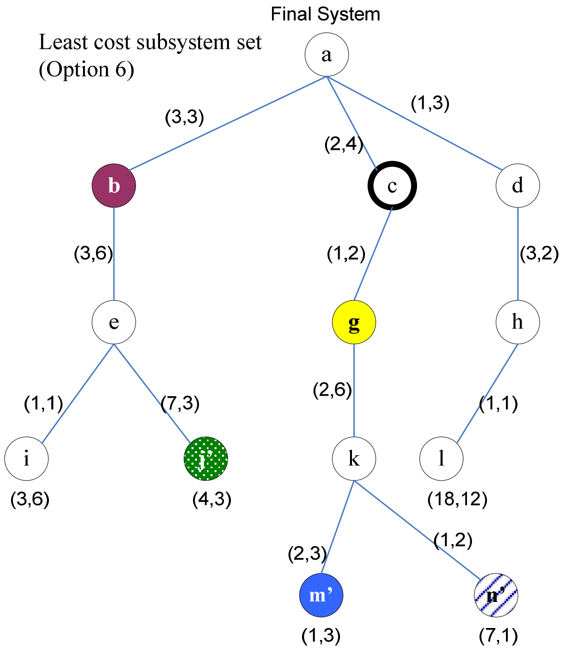

Fig. 16. Least cost subsystem set.

The non-dominated set of design options allows developers to eliminate alternatives that are clearly impractical, according to existing budgetary constraints. If the development cost of this system is limited to a certain threshold irrespective of the acquisition duration, all options with higher cost than this threshold can be eliminated. For instance, if the value of the cost threshold is 50, only design options within that threshold are considered for further analysis.

Pareto Optimal Output File

The Pareto optimal output file is a ranked list of seven subsystem sets arranged in order of importance to the design criteria.

1. (52,65) subsystems: (*b′*, ***f*** , *n’*, *m*, *k*, *g*, ***c***, *l* , *h*, *d*)
2. (61,60) subsystems: (*b*, *e*, *i*, *j'*, *n'*, *m*, *k*, *g*, *c*, *l*, *h*, *d*)
3. (65,59) subsystems: (*b*, *e*, *i*, *j*, *n'*, *m*, *k*, *g*, *c*, *l*, *h*, *d*)
4. (49,71) subsystems: (*b’*, ***f*** , *n*, *m*, *k*, *g*, ***c***, *l* , *h*, *d)*
5. (51,66) subsystems: (*b'*, ***f*** , *n'*, *m’*, *k*, *g*, ***c***, *l* , *h*, *d*)
6. (60,61) subsystems: (*b*, *e*, *i*, *j'*, *n'*, *m'*, *k*, *g*, *c*, *l*, *h*,*d*)
7. (48,72) subsystems: (*b'*, ***f***, *n*, *m'*, *k*, *g*, ***c***, *l*, *h and d*)

Subsystem sets 1, 4, 5 and 7 are immediately eliminated from consideration due to components ***f*** and ***c*** being incompatible. The list is Pareto sorted by two objectives: cost and schedule. The result is listed in Table 1.

Evaluating the feasible options, the least cost is subsystem set 6 and the shortest schedule is subsystem set 3. The optimal combination of least cost and least schedule is either set 6 or 2, if both cost and schedule are equally important. The Pareto optimal output file is adequate to support the methodology.

Results in Terms of the System Architecture

In terms of the communication system example, design option 3 is the fastest-to-develop. Design option 6 (least-

Table 1. Pareto optimal list of subsystem sets: cost and schedule.

Subsystem Set	Cost	Feasible?
7	48	NO
4	49	NO
5	51	NO
1	52	NO
6	60	YES
2	61	YES
3	65	YES
Subsystem Set	**Schedule**	**Feasible?**
3	59	YES
2	60	YES
6	61	YES
1	65	NO
5	66	NO
4	71	NO
7	72	NO

cost) calls for nearly the same components as option 3, with the only exceptions being the channel processing/control unit (*j*') replaces (*j*), and the software processing unit (*m*') replaces (*m*). Alternate subsystems *b*' and *g*' are eliminated from design options, as well as components *f* and *n*. The result is that option 3 can be developed for 2 units of duration faster than option 6, but option 6 can be developed for 5 less units of cost than option 3. These options then fall into the trade space for decisions based on programmatic objectives and constraints. The resulting architecture is presented in Fig. 17.

CONCLUSIONS

This paper presents a methodology and multi-objective framework for modeling the subsystem selection process for subsequent inclusion into helicopters, categorized as complex systems. The system is defined in terms of a hierarchal structure describing all candidate subsystems along with their technical and budgetary interfaces. This structure is represented in the form of a directed acyclic graph with its nodes and arcs comprising the different subsystems and their interfaces, respectively. The costs of the arcs are taken as the cost of interfaces they represent, which is described in terms of a set of attributes including monetary cost, duration of acquisition, performance, and risk. A multi-objective shortest path algorithm is then applied to generate the set of non-dominated paths in this graph. Each path represents an integrated set of subsystems available to the system or the final product. The model is applied to a hypothetical real-world system with 18 candidate subsystems. The solution presents seven non-dominated integration schemes, from which the least-expensive and the fastest-to-develop design options are identified.

Effort is on-going to develop the methodology and graph theoretic model for broader systems integration problems beyond product development, where business constraints and considerations are expanded. This includes developing the case for subsystem selection precedence (if *a* then also *b*), multiple choices versus limited choices (e.g., the system is required to be compatible with heritage technology), dependency constraints using mutual exclusivity, and interfaces linked to other fundamental activities (support, training, test equipment, development tools, etc).

Military helicopter development from a COTS platform can benefit from the systems engineering methodology described in this paper by considering performance parameters and risk as arc attributes along with cost and duration. Key performance parameters such as hover out-of-ground effect (HOGE), endurance, range, transportability, etc., have an associated cost, schedule, and risk when integrated as a new platform. Insert the uncertainty of COTS and MOTS subsystem integration, and the development problem quickly becomes complex and multi-objective.

Design synthesis, using graph theory and a multi-objective shortest path algorithm, assist the trade analysis process by simultaneously considering multiple technical and budgetary objectives during subsystem selection. Specifically, helicopter systems are developed with less risk to redesign by optimally selecting the subsystem foundation at

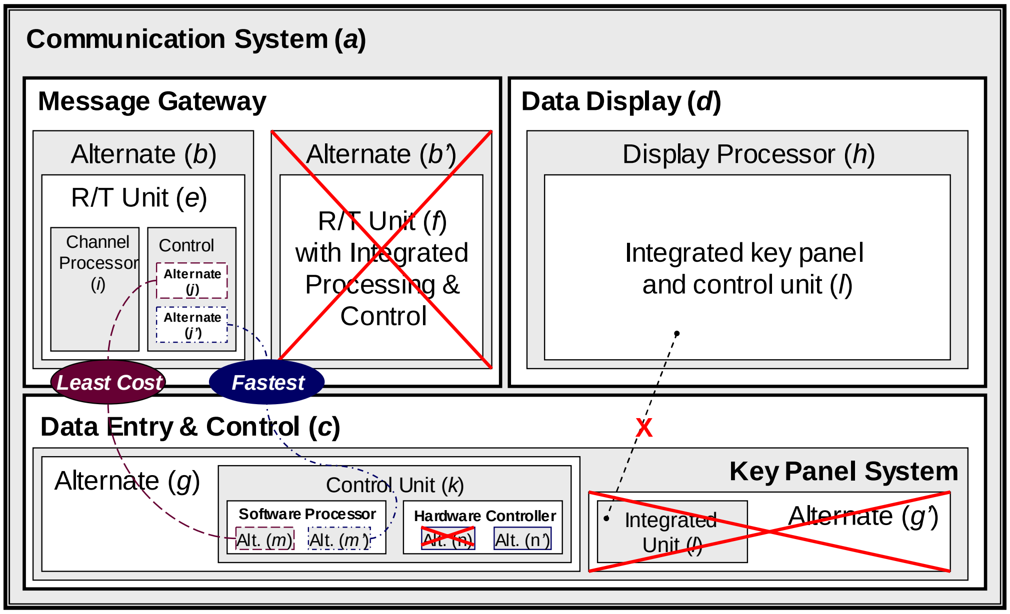

Fig. 17. Resulting architecture for least cost and fastest to develop.

preliminary design, thus reducing overall project cost and duration. The modeling framework merges multiple system objectives to form a solution set of alternative design paths and integration schemes from which an optimal set of subsystems can be selected.

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