# System of systems force structure optimisation

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## ABSTRACT

A system of systems study plan was developed and a prototype was executed to optimise a recommended military force structure. This methodology defined the optimal force structure, using constrained optimisation to reflect budget limitations and desired mission performance. The force structure included surface and air assets, a command, control, communications, computers, intelligence, surveillance and reconnaissance (C4ISR) architecture, and a recommended logistics infrastructure. A second aspect of the study plan defined the total acquisition strategy, which accounted for: retiring legacy assets, extending the service life of existing assets until new replacements became available, and acquiring new assets for deployment, within the budget allocation. This methodology combined various modeling and simulation techniques to meet three study objectives. First, a non-linear mixed integer programming model maximised performance, subject to cost constraints, cost as an independent variable (CAIV). Second, a dynamic programming model scheduled the transition from the legacy force structure to the future force, defined by the previous modeling technique. Third, a process simulation model simulated performance, over a one-year time period, for 25 areas of responsibility and five missions. This model verified performance estimates generated by the previous models.

## 1.0 INTRODUCTION

As the United States Coast Guard (USCG) surveyed its rapidly aging fleet of ships and aircraft, as well as a deteriorating basic infrastructure (including shore facilities, ports, air bases, and outdated communications equipment and methodology), it recognised the need to modernise its force structure. This challenge demanded an analytical systems approach that could assist the USCG in meeting its modernisation objectives of maximising mission performance while minimising cost.

Providing this evaluation tool for the Coast Guard represented the US Coast Guards, and Boeing's first effort to develop a system of systems approach to designing a military force structure. Standard operations research techniques provided the analytical rigour necessary to substantiate the force structure.

## 2.0 ANALYTICAL PROCEDURE FOR SYSTEM OF SYSTEMS DESIGN

The USCG system of systems began with the methodical decomposition of missions to derive mission requirements, which were passed along to integrated product teams (IPT) for detailed evaluation. Throughout the entire design process, mission decomposition provided insight regarding customer business practices and helped identify critical technologies that would enhance mission performance. In addition, this technique generated information concerning the costs, risks, and effectiveness associated with each new technology, which enabled the customer to intelligently decide which technologies to purchase and deploy.

Figure 1 illustrates the elements of the force structure evaluation. The methodology consists of five major components, including: (a) mission analysis and requirements generation; (b) analysis of alternatives and technology insertion; (c) configuration synthesis and risk assessment; (d) implementation; and, (e) verification of performance and cost. The following section describes each of the procedures and the expected results.

### 2.1 Mission analysis

The Coast Guard provided thirteen primary missions for consideration during this study. These missions are detailed in Fig. 2. An internal assessment of the missions identified six major missions as constituting ninety-five percent of Coast Guard activity. Therefore, these six missions provided the basis for the majority of the study. Although the other seven missions were not specifically modeled, the capability to

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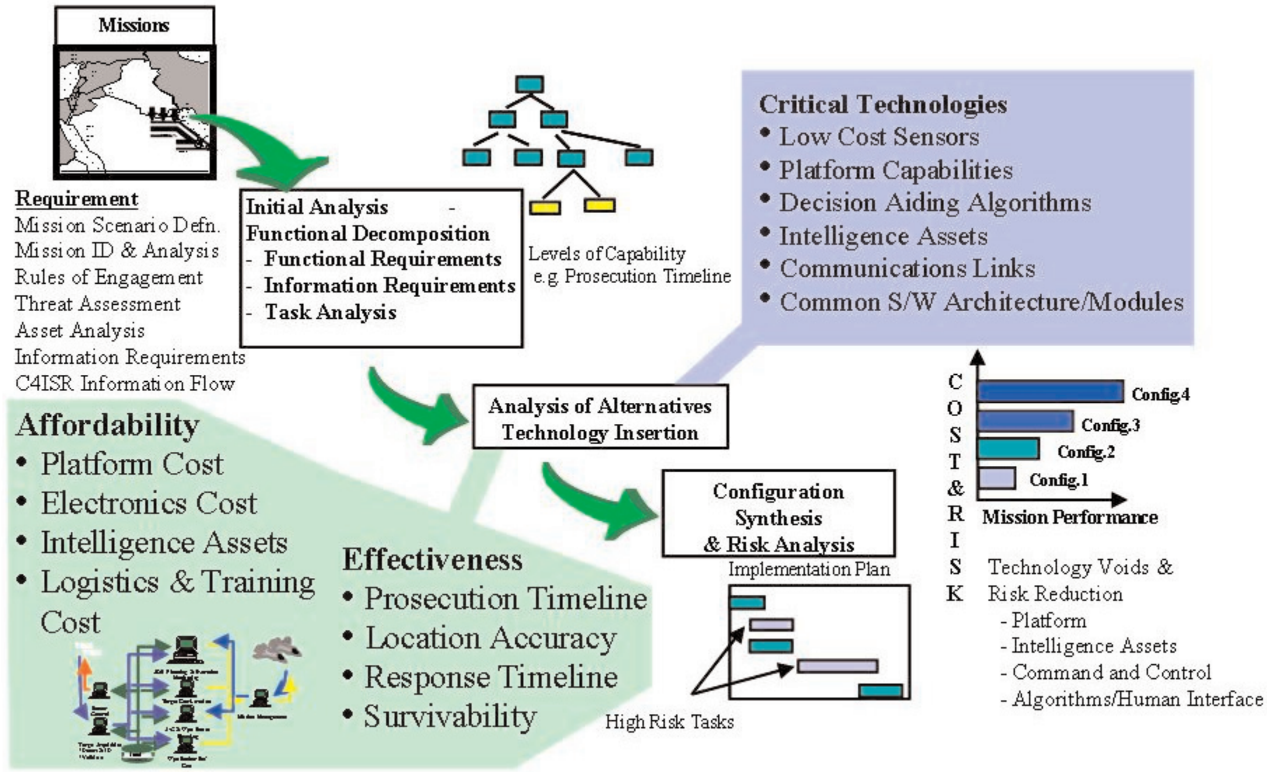


Figure 1. Elements of force structure evaluation.

perform those missions was retained in this study, to assist the USCG in defining and acquiring the appropriate future force structure required to perform all thirteen missions in the most cost-effective manner. This study plan details the method used to accomplish this task.

The purpose of mission decomposition was to determine the critical functions and tasks that must be performed to satisfy each mission. With this information, measures of merit (measures of task success) were defined and candidate technologies required to perform the tasks and functions were identified. Trade studies (analyses of alternative systems) were performed to select the most effective technologies for use within the force structure. The mission analysis procedure consisted of several steps. As an example, Fig. 3 illustrates the mission components for one of the six major USCG missions — anti-smuggling. The 'Execute Anti-Smuggling' mission was broken down into four major functions: search and detect targets, process target information, intercept the target, and finally, prosecute the target. A 'target' is defined as any person or vessel attempting to smuggle contraband into the USA, such as illegal drugs or illegal aliens. The decomposition procedure continued to another level of detail as the 'Process Target' function was subdivided into five components. 'Correlate Target Track' described the process of determining if the target track was already in the database or new. If it was new, it had to be added to the database. If the track was not new, it must be fused with the existing track database. This procedure included updating the track information on target: identification, location, heading, and speed. Once the track list was updated, then it was prioritised. The Coast Guard considered five missions of highest merit: search and rescue (priority one), anti-drug and illegal alien migration (tied for priority two), fisheries and general law enforcement (tied for priority three). When the track list was prioritised, the top priority target was assigned to the next asset (e.g., ship, helicopter, etc.) or group of assets available to intercept and prosecute that target. Finally, target assignment was communicated to the asset for prosecution.

After mission decomposition was complete mission analysis followed, as illustrated in Fig. 4. The first column of this matrix lists the mission task. The colour coding for each task conveys the function to which that task contributed. The second column identifies the specific information necessary to perform each task. (Another column could be added detailing the source of the information.) Next, column three identifies the output generated during task execution. This output may very well be information that is used in a succeeding task. The fourth column, entitled 'measure of effectiveness,' represents indications of the relative success of task execution. In addition, these measures of effectiveness made allowances for estimated task performance requirements. These estimated requirements actually represented the minimum threshold for task performance and served as indicators used to evaluate different systems of performing the tasks. Next, the 'primary responsibility' column details which systems and operators were responsible for performing the task. This information established the baseline for comparing new technologies and systems, so that the trade study process could provide meaningful comparisons regarding which new systems would best replace existing technologies and systems, represented by the baseline. The final column in the matrix identifies which IPTs (groups of experts) proposed the appropriate replacement systems or capabilities to substitute for the baseline.

This mission decomposition process served as the foundation for identifying requirements for the system of systems. After identifying missions, developing mission scenarios, and analysing those missions, many derived requirements were determined. In addition to identifying information requirements, the source of information was determined, which helped ensure that information was received by the unit in a timely and accurate manner. Rules of engagement were identified for the baseline system and modified, as needed, to accommodate any new technology introduced into the force structure. As missions


Figure 2. Primary Coast Guard missions.

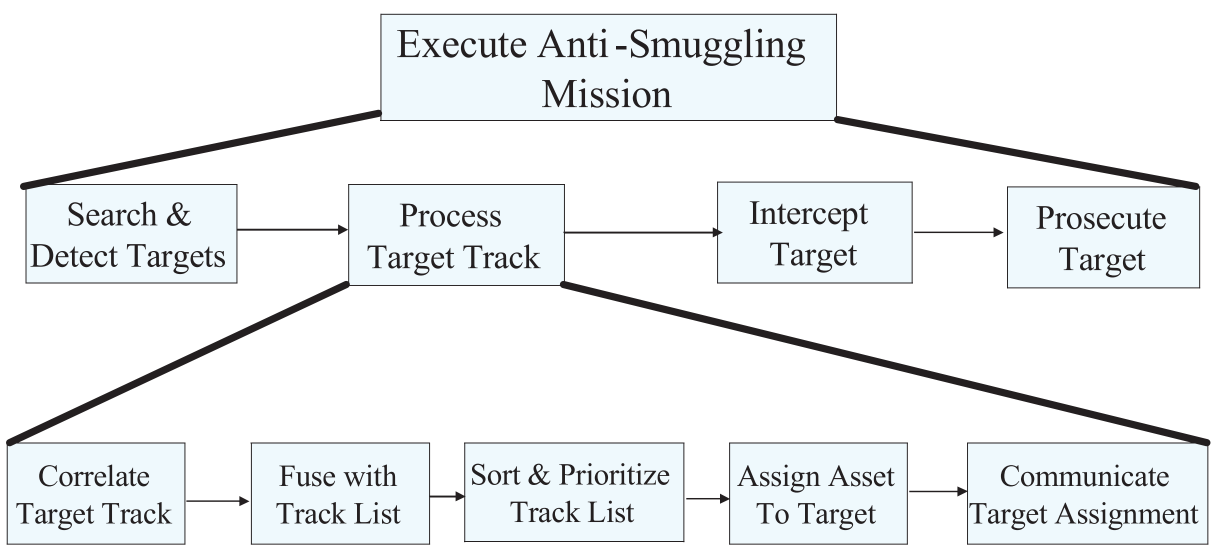


Figure 3. Mission decomposition example.

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| | Task | Information Required | Output | Measure of Effectiveness | Primary Responsibility | Tentative IPT Responsibility |
|---|---|---|---|---|---|---|
| 1 | CTU on Patrol in AOI<br>CTU On Patrol in AOI | Current Assigned AOI<br>Intel on potential threats<br>Assigned Patrol Pattern<br>Assign Patrol Assets<br>Assigned Capabilities | Presence per time period<br>Deterrence | Time on Station | Dist HQ/ CTU Commander | C4I<br>Surface<br>Air |
| 2 | Sensor Search for AOI Contact<br>Sensor Search for AOI Contact | Area to be searched<br>Asset types and capabilities<br>Tracks detected<br>Tracks sorted<br>Tracks correlated | Contact to be processed | Contacts Processed | CTU Commander | C4I<br>Surface<br>Air |
| 3 | Off Board Sensor Contact from CTU Assets<br>Off Board Sensor Contact from CTU Assets | Area to be searched<br>Asset types and capabilities<br>Tracks detected<br>Tracks sorted<br>Tracks correlated | Contact to be processed | Quality of data<br>%time false alarm<br>Time on Search | Offboard Asset/CTU | C4I<br>Surface<br>Air |
| 4 | Contact from Onboard Sensor<br>Contact from Onboard Sensor | Area to be searched<br>Asset types and capabilities<br>Tracks detected<br>Tracks sorted<br>Tracks correlated | Contact to be processed | Quality of data<br>%time false alarm<br>Time on Search | CTU Commander | C4I<br>Surface<br>Air |
| 5 | Off Board Sensor Contact from Non-CTU Assets<br>Off Board Sensor Contact from Non-CTU Assets | Area to be searched<br>Asset types and capabilities<br>Tracks detected<br>Tracks sorted<br>Tracks correlated | Contact to be processed | Quality of data<br>%time false alarm<br>Time on Search | Offboard Non-CTU Asset | C4I<br>Surface<br>Air |
| 6 | Communication: Voice, Data Link<br>COMM | Sensor Contact by Offboard, CTU Asset | Status of Contact<br>TGT Info (Tenative)<br>- Type, Position, Speed, Cours | Successful Comm<br>Que time of track data<br>Transmission time | Offboard CTU Asset | C4I<br>Surface<br>Air |

Figure 4. Mission analysis example.

were analysed, the threats were identified and analysed to determine their potential impact on mission success and to assess vulnerability of the baseline and future assets to those threats. Also, asset analysis was performed to fully understand their capability to perform the missions. The following examples represent the types of analysis that helped identify requirements and measures of effectiveness and performance.

Examples of measures of effectiveness for each mission function include the following: (1) Search and detection (sensor coverage over time, probability of detection of different types of targets, and number of targets detected); (2) Process of information (number of tracks maintained in the database, communications bandwidth, timing of track correlation, timing of track fusion, quality of track correlation, and quality of track fusion); (3) Target interception (probability of successful target intercept with each system, expected timing of intercept, number of targets missed, and asset utilisation); and (4) Target prosecution (probability of successful target prosecution, number of targets successfully prosecuted, number of targets unsuccessfully prosecuted, and resource utilisation).

### 2.2 Analysis of alternatives and technology insertion

Once the mission analysis was completed, the integrated product teams used the requirements derived and reported in the matrix (Fig. 4) to identify alternative systems and technologies as baseline system replacement candidates. The IPTs conducted trade studies to identify which systems best met the requirements for the tasks. For each task, the IPTs generated a ranking of systems or technologies required to perform the task. The systems engineering team, in turn, used the ranking for the system synthesis. In order to evaluate and compare system candidates or technologies, the measures of performance defined during the mission analysis were employed.

### 2.3 Configuration synthesis and risk assessment

In order to identify the appropriate combination of systems (e.g., watercraft, aircraft, base location) and technologies for deployment as the future force structure, a method had to be formulated to select these systems. During the analysis of alternatives, the IPTs selected and recommended the apparent best system for performing each task. The IPTs discovered that some systems operated more synergistically with other systems which was not intuitive obvious to the experts. Therefore, at times, the second most-preferred aircraft was combined with the best ship to comprise the best cohesive command task unit.

In order to select and combine systems and technologies, the IPTs used a simulation modeling method called 'non-linear mixed integer programming.' This was a constrained optimisation technique in which the decision variables included the number of air assets, surface assets, C4ISR components, and logistics components recommended for the force structure. In this case, the customer identified the constraints as the budget allocations for acquisition, operation, and maintenance of the recommended force structure changes, as well as satisfying the minimal mission performance requirements. The objective function was defined to minimise the cost per mission subject to the above stated constraints. Once this technique was developed and employed, additional information became apparent, including the sensitivity of substituting different systems for those selected by the optimisation algorithm. This sensitivity analysis helped identify the risks to cost and technology availability. When the sensitivity analysis detected significant risk, the IPTs developed a mitigation plan for eventual substitution of alternative systems. In this way, non-linear mixed integer programming assisted the USCG in choosing its force structure for the future. The next step involved determining the most effective way to acquire the recommended combination of systems, over a 20-year planning horizon. This need led to the implementation planning procedure.

## 2.4 Implementation

The protracted time frame (20 years) for implementing the Coast Guard's desired force structure necessitated scheduling the retirement of legacy assets; upgrading legacy assets, as needed, to keep them operating until replacement assets could be acquired; and finally, acquiring the new assets. Yearly limits on the USCG's acquisition budget posed the major challenge to this procedure. Therefore, the Coast Guard requested a method to assist them in determining when to upgrade, retire, and replace each system. Additionally, the customer required assurances that mission performance would not deteriorate during the acquisition period. This led to using another operations research technique, dynamic programming.

Dynamic programming is a computational method for solving optimisation problems, including those in which the variables are continuous as well as discrete. In order to solve a problem with $n$ independent variables, the dynamic programming technique breaks the problem into a series of $n$ sub-problems, each containing only one variable. In the USCG case, the multi-variable problem involved determining the number of assets to buy over a twenty-year period. The dynamic programming method converted this long-term, overall acquisition goal into sub-problems, each of which identified the number of assets to acquire in each individual year. These sub-problems were solved sequentially in such a way that the combined optimal solutions of the n sub-problems yielded the optimal solution for the original, 20-year problem of acquiring a new USCG force structure. This technique reduced the massive problem to a computationally simpler problem series, while adhering to the constraints described. However, following the optimisation process, it was necessary to verify the theoretical ability of each system to meet actual performance and cost objectives.

## 2.5 Verification of performance and cost

Once the optimal force structure was defined for the 20-year period, a simulation model was developed to help verify performance and cost. This discrete event simulation predicted the number of missions that the given force structure could perform during each quarter of a year. Annual performance was sub-divided into quarterly segments to account for seasonal weather patterns and their effects on the targets. During the winter, less smuggling activity occurred, due to inclement weather, but search and rescue missions noticeably increased. During the warmer months, smuggling increased. The model identified which specific assets were more suitable for these different types of mission. In addition to estimating the number of missions performed, the model estimated the cost of operations and resource utilisation. This helped determine the ability of a given force structure to meet given performance and cost requirements. When those requirements were not met, new force structure alternatives were developed and fed back to the optimisation algorithm, which, in turn, recomputed the problems and performed the verification procedure again. This iterative process continued until each component of the force structure was finalised.

# 3.0 SUMMARY AND CONCLUSION

The system of systems study plan can be considered as a continuous cycle of analysis, design, and force structure updating. Several simulation models helped define the optimal combination of assets the USCG should acquire during the 20-year term of the system integration process.

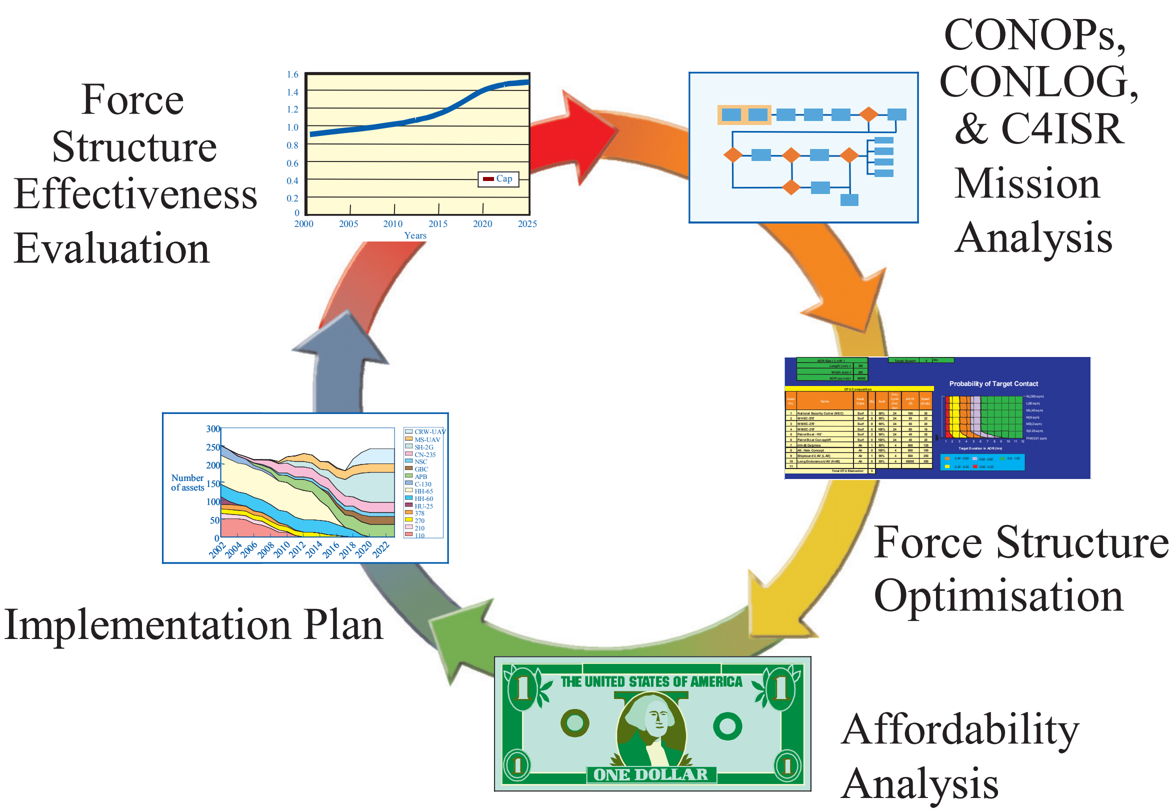


Figure 5. Iterative analytical components.

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Once the implementation plan was completed, effectiveness analysis was performed to ensure that mission effectiveness goals and criteria were met. This included determining the deployment schedule, creating the maintenance schedule, and adhering to the limited performance capabilities of all assets, both legacy and new. After defining the deployment schedule, simulation techniques evaluated mission performance over a year-long period. The measures of merit were the successfully completed missions. Mission success measures were compared to system specifications and, when necessary, returned to the design team for additional analysis and refinement.

By using conventional operations research techniques of statistical analysis to summarise information and evaluate missions, the IPTs developed optimisation methods for defining the force structure and scheduling the acquisition, modernisation, and retirement of legacy systems. Finally, simulations were used to evaluate the effectiveness of the force structure. Together, these methods comprised a system of systems analysis and synthesis approach to solving the USCG's force structure modernisation challenge. Subsequently, this system of systems approach has been applied to several other customer programs. The unique feature of this technique is its ability to use standard systems engineering methods in conjunction with operations research techniques to provide an analytical basis for defining a system of systems and to verify that the derived results actually meet all customer requirements.

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## Erratum

# A theoretical description of viscous flow along a flat plate

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formerly Royal Aircraft Establishment, UK

p 585, col 2, equations (1),

replace "$2\,(p-p_0)/p_0 u_0^2$" by "$2(p-p_0)/\rho_0 u_0^2$"

p 586, col 1, 14th line,

replace "$\partial^2/\partial X^2+\partial^2/\partial X^2$" by "$\partial^2/\partial X^2+\partial^2/\partial Y^2$"

p 587, col 1, equation (23),

replace "$(X-t_2)$" by "$(X-t_1)$"

col 2, 3rd line,

replace "Equa tions (3)" by "Equation (3)"

p 589, col 1, bullet point 2,

append the se ntence "The first approximation consists of drag poles only."

col 1, bullet point 3,

delete the se ntence "The first approximation consists of drag poles on ly."

col 1, Reference 7,

replace "Z a gnew" by "Z. angew"

col 1, Equation (A2)

delete "(" before "$Y/R_m^2$" and ")" after "$K_1(R_m/2)$"

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