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QUANTITATIVE MODELS FOR PERFORMANCE AND COST OF COMMAND, CONTROL, COMMUNICATIONS, COMPUTERS AND INFORMATION SYSTEMS

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ABSTRACT

Quantitative models of performance and cost for Command, Control, Communications, Computers and Information Systems were built to create viable force development options to help transform the Canadian Forces. A humanitarian operation was used as an example scenario and was broken into vignettes and tasks. The primary tool used to analyze the performance of these tasks was the decision cycle functions of orient, evaluate, decide and implement. It was assumed that the time available to complete this cycle was tightly constrained for each task in the scenario. The status quo performance was given a nominal value based on the personnel available and the current configuration of technologies. Future technological options will streamline processes, making various systems interoperable by improving communications and information processing hardware, and decision support software. Costs were estimated using models of capital investment, operations personnel and maintenance factors. Force development options were constructed based on the possible tradeoffs between technology and personnel. It was demonstrated that, by introducing new technology, quantifiable performance improvements could be achieved while keeping costs constant, or alternatively, significant cost savings could be obtained without loss in performance.

1. Background

Force development within the Department of National Defence is a three-stage process of capability-based planning, capability management and capability production. It is a top-down approach, starting from the strategic level that marks a significant departure from the former threat-based method of force development [1]. A capability is a combination of people, processes and technologies allowing the Canadian Forces to act in a specific way to achieve a specific mission. The scenario is a description of the events leading up to, and including, the mission, along with its desired outcomes.

Capability engineering, which employs the 'best practices' of systems engineering [2], is defined as a set of ordered activities using a collaborative, systematic, disciplined and quantifiable approach involving people and technologies to produce a desired capability. It is designed to provide decision makers with system-of-systems options for force development [3]. The capability engineering process that will be discussed in this paper was applied to the Command, Control, Communications, Computers and Information capability in a major domestic humanitarian assistance disaster relief scenario encompassing a metropolitan area [4]. This scenario was divided into smaller vignettes for analysis. The vignette described in this paper involves liaison and assistance to law enforcement agencies, and consists of seven distinct Command and Control tasks.[1]

In the capability engineering process, there are operational research analysts responsible for developing a capability engineering decision framework with which to conduct trade-off studies for force development options of people, processes and technology. The capability engineering decision framework is a tailored set of quantitative models to examine force development options in terms of performance, cost, schedule, and risk. The following subsections describe the models and their implementation, with the performance and cost models described in the most detail.[2]

2. The Performance Model

It was decided that performance of the Command, Control, Communications, Computers and Information capability would be measured according to how well decisions were made at the Operational Headquarters. Decision-making was broken down into the functions: orient, evaluate, decide, and implement.[3] Together, these four functions form a decision cycle.[4] A decision is defined as the outcome of this cycle. Three main aspects contributing to decision quality were considered to be information availability, information analysis, and decision cycle time.

Information availability is required for decision-making. Without any information, there is no basis for decision-making. With some information, a decision may be possible. With more information, better decisions can be made. It was assumed that more information always increases decision quality, but in a diminishing returns fashion. That is, an additional unit of information delivers more improvement when the total amount of available information is relatively small and less improvement when the information total is already large.

Information analysis is also required for decision-making. Without analysis, decisions would be no better than if done randomly. With some analysis, decisions can be improved. It was assumed that more analysis always increases decision quality but, as in the case of information availability, improvements scale in a diminishing returns fashion.

Once initiated, decision-making is assumed to be a repetitive process. The decision cycle time depends upon the tasks and functions being executed within a particular vignette, and on the specific resources—people, process, and technology—available. The headquarters must produce a decision within a constrained time related to the tasks. Decision quality is therefore dependent on the

[1] The seven vignette tasks are: (i) establish and maintain contact with law enforcement agencies; (ii) initiate flow of information for the disaster zone; (iii) assist with coordinating employment of civil mobility resources; (iv) assist in crowd control; (v) conduct or assist with humanitarian aid/disaster relief distribution; (vi) assist with policing operations as required and provide assistance to minimize looting; and (vii) handover resources and responsibilities to civilian authority at closure.

[2] Alberts and Hayes [5] Chapter 7 has a similar although qualitative discussion of assessing alternative command arrangements and Figure 22 in their book describes how life-cycle cost estimates would be employed as well as scenario performance to determine system utility.

[3] This is the Operational Headquarters equivalent to the more tactical observe, orient, decide and act [OODA] loop concept of decision making attributed to military strategist Col. John Boyd of the United States Air Force.

[4] Alberts and Hayes [6] discuss the cyclic approach to Command and Control as one of six approaches to the development of mission specific directives by an operational headquarters (pp. 20-21).

relationship between decision cycle time and constrained time. For instance, if decision cycle time exceeds the constrained time, there will be insufficient time to completely execute all four functions—orient, evaluate, decide, implement—and decision quality will be low. Assuming that the expected orient, evaluate, decide and implement functions are conducted in the decision cycle time, decision quality will increase as the ratio of decision cycle time to constrained time decreases. If decision cycle time falls below constrained time, then more than one decision cycle will be possible. In that case, headquarters will refine the decision. Thus, each additional partial or complete decision cycle delivers an improvement in decision quality.

While increasing information can increase decision quality (because there is more data on which to base decisions), there is a price associated with information increase. Since it takes additional time to collect, analyze and disseminate additional information, increased information availability comes at the cost of increased decision cycle time. However, increasing the decision cycle time to constrained time ratio decreases decision quality. Therefore, a mechanism allowing information increase while maintaining or reducing decision cycle time is desired. This is where communications technology, decision support technology and skilled personnel come into play.

It was recognized that the variables associated with a force development option—communications and decision support hardware and software technologies, and number of skilled personnel of different types—contribute to headquarters decision quality. Communications technology is used to collect information upon which decisions are made, and disseminate orders based upon decisions. Better communications systems increase the efficiency of the 'orient' and 'implement' functions, thereby reducing decision cycle time. Decision support technology is used to analyze collected information. Better decision support systems therefore increase the efficiency of the 'evaluate' and 'decide' functions, reducing decision cycle time. However, while improvements can be realized by introducing new systems, there is a downside to increasing their total number, because each additional system increases the administrative workload of the personnel in the headquarters. One should only be introduced if the increased functionality more than compensates for additional administrative workload. Optimally, new communications and decision support technologies will integrate two or more existing systems, while at the same time adding functionality.

Meanwhile, skilled personnel can be used for information collection, analysis, decision, and dissemination. Personnel therefore contribute to all four functions within the decision making process. The performance model assumes that personnel are employed optimally, and that adding more skilled personnel effectively reduces decision cycle time and improves decision quality, but in a diminishing returns fashion.

2.1 The Force Development Options

There will be three force development options considered in the analysis below: the status quo option which involves a hardware and software refresh of the current systems used in Command and Control at the Operational Headquarters; option 1 which involves an investment in hardware and software to develop a collaborative information environment at the Operational Headquarters; and option 2 which involves an investment in hardware and software to develop a secure wireless broadband network to move the collaborative information environment to the tactical level. The number of personnel employed at the Operational Headquarters is estimated to be 70 for the status quo option. In option 1 and option 2, it will be assumed that this number can vary but should not exceed 70. It will also be assumed that the performance of options 1 and 2 should not be less than the status quo option's performance. Then, if less people are used in the Operational Headquarters for either of these two options, the performance should be at least as good as what can currently be obtained with the status quo with 70 people.

2.2 Performance Model—Figure of Merit Concept

The performance model considers information availability, information analysis and decision cycle time, along with communications technology, decision support technology and skilled personnel, to examine decision quality. The decision quality considered the complete task list and assumed all tasks were being executed concurrently. This meant an Operational Headquarters would be processing many decision cycles at the same time. Since the workload differed from task to task, personnel were allocated in proportion to task workload.

Communications and decision support technologies were guided by the choice of force development option. Individual force development options were therefore provided as sets of personnel, communications and decision support technologies.

To conduct trade-offs in developing the force development options, one needs a way of quantifying the expected performance obtained from each option. The performance model provides a figure of merit to represent the decision quality of a force development option, denoted Q, with a numerical value in the range $(0,1)$. A value of $Q=0$ means the decision quality is zero, and a value of $Q=1$ means perfect decision quality. Here one unit of data is assumed to be the data collected and disseminated when the time allocated to these functions is exactly equal to the requirement. Similarly, one unit of processing occurs when the time spent processing and deciding is exactly equal to the requirement.

2.3 Performance Model—Quantitative Description

It was decided to combine the 'orient' and 'implement' functions into one model that will estimate the time taken to collect data and disseminate decisions using the communications technology in the force development option. It was also decided to combine the 'evaluate' and 'decide' functions into a single function which would model the time spent utilizing decision support application computers and software available in the force development option. Meanwhile, personnel are a flexible resource that can be applied to both the communications and decision support tasks to maximize the overall decision quality. Thus, there is a need for a communications sub-model to estimate the collection of data for use in the decision analysis and a decision support sub-model to estimate the efficiency of the information processing.

The primary method of analyzing the activities of the scenario is through the functional decomposition of the vignettes into a task list.[5] Consider the decision cycles and the time constraints involved in various tasks. This is particular to the Command and Control capability and will be a major factor in the overall decision quality.

It is assumed that fractional amounts of personnel time can be allocated incrementally to the communications and/or decision support part of the tasks as necessary to improve the decision quality. With more personnel added to the task optimally, more data can be collected or analyzed to support the decision. Communication systems can

[5] Albert and Hayes [6] discuss that common application of 'divide and conquer' decomposition in the development of Command and Control procedures (pp. 38-39).

automate the data collection process and thereby collect more data, and effective decision support applications can process the data faster and/or better with the same amount of personnel time.

It will be assumed that each task involves a decision and that each decision will have a cycle time that may limit the quality of the decision. With more time between decisions, there is more time to collect and analyze information and thereby produce a better decision.

2.3.1 The Communications Sub-model

With a particular group of communications systems and manual processes, a certain amount of data can be collected and disseminated in a certain amount of time. Within a decision cycle, there is a situation of diminishing returns in the amount of data that can be collected and disseminated. If more automated systems are added, then more data can be collected and disseminated in the same amount of time. If more personnel are added optimally, then more data can be collected and disseminated in the same amount of time. If more time is available, then more data can be collected and disseminated. Also if one can reduce the number of systems, thereby merging subtasks while collecting and disseminating the same amount of data, one can free up personnel for additional data collection and dissemination. Thus, reducing the number of unique systems is a good objective.

The following parameters are input to the communications sub-model. Let t_i be the decision cycle time in hours for task i. Let $T_{c,i}$ be the personnel hours required to collect and disseminate one unit of data for one decision for task i in the vignette with support of the communications technology in the force development option. Let $P_{c,i}$ be the allocation of personnel assigned to data collection or decision dissemination for task i with the configuration of hardware and software associated with this force development option. Thus, the amount of data collected is:

$$D_i = P_{c,i} * t_i / T_{c,i} \,.$$

2.3.2 The Decision Support Sub-Model

The more data collected, the more time is required to analyze it. Thus, based on the number of personnel and the time required to conduct the subtasks with a certain configuration of decision support applications, one can compute the number of processing cycles that can be conducted within the decision cycle. Thus, more information makes for better decisions, in general, but more personnel and decision support applications can allow for more time to analyze data or repeat analysis inside the decision cycle and thereby improve decisions.

Let $T_{s,i}$ be the personnel time required to process one unit of data and turn it into one unit of information and make a decision with this information in task i in the vignette with decision support application hardware and software associated with the force development option. Let $P_{s,i}$ be the allocation of decision support personnel assigned to task i. Then the number of processing cycles is computed as:

$$C_i = P_{s,i} * t_i / T_{s,i} \,.$$

2.3.3 Decision Quality Model

The quality of the decision within one decision cycle for this task is modelled using a lognormal function so that one unit of data and one cycle of processing produces the information necessary to generate a $Q_i = 0.5$ decision.

The figure of merit function is:

$$Q_i = \Phi(\ln(D_i * C_i)) \,,$$

where Φ is the standard normal distribution function and ln is the natural logarithm function. This results in a diminishing returns situation when more person hours are assigned to the various functions in the decision cycle.

2.3.4 Performance Model Validation

Since this model of performance is intended only to provide a figure of merit with which to examine variations based on configurations of technology, processes and people, the validation of the model was only conducted to ensure that the figure of merit performed as expected with various changes to the data. That is, a simple sensitivity analysis with the model was conducted to ensure that the changes in the output were intuitively logical. Table 1 provides a sensitivity analysis for a single task in which the nominal values were set at a task time (t_i) of three hours, a data collection and decision dissemination time $(T_{c,i})$ of three person hours, an information processing and decision time requirement $(T_{s,i})$ of three person hours, with three people assigned to the data collection and decision dissemination functions $(P_{c,i})$ and three people assigned to the information processing and decision functions $(P_{s,i})$. For this nominal case as seen in the middle column of Table 1, the figure of merit for the decision quality is 0.986. Then the values were individually allowed to vary between one and five. So when the task time $t_i = 2$ hours and all the other variables are held constant at 3, the figure of merit is 0.917 compared to the original value of 0.986.

2.3.5 Performance Data

Table 2 provides the estimates of the time required to execute the seven tasks associated with the liaison and assistance to law enforcement agencies vignette in this humanitarian assistance disaster relief scenario. Each task is divided into collection and dissemination, and processing and decision functions according to the grouping of the orient, evaluate, decide and implement functional decomposition. These estimates, based on the complexity of the scenario, vignette and tasks, were provided to the operational research analysts by a subject matter expert for Command and Control. The decision cycle time (t_i) was given as four hours for all of the tasks in this vignette. Furthermore, it was assumed that all of the personnel in the headquarters work 12-hour shifts.

Sensitivity Variables	1	2	3	4	5
Task Hours (t_i)	0.500	0.917	0.986	0.997	0.999
Collection Personnel $(P_{c,i})$	0.864	0.963	0.986	0.993	0.996
Processing Personnel $(P_{s,i})$	0.864	0.963	0.986	0.993	0.996
Collection Hours Required $(T_{c,i})$	0.999	0.995	0.986	0.972	0.954
Processing Hours Required $(T_{s,i})$	0.999	0.995	0.986	0.972	0.954

Table 1: Performance figure of merit for decision quality based on a single task with nominal values 3 and sensitivity analysis values varying from 1 to 5.

2.3.6 Performance Model Results

When all the tasks are included in the vignette and the allocation of personnel to the tasks and functions done so as to maximize the figure of merit subject to a personnel constraint, the results in Table 3 and Figure 1

Vignette Tasks	Status Quo	Option 1	Option 2

(i) establish and maintain contact with law enforcement agencies	Collect: 5.25 Process: 7.00	4.0 5.25	3.5 4.5
(ii) initiate flow of information for the disaster zone	4.5 6.0	3.5 4.5	3.0 4.0
(iii) assist with coordinating employment of civil mobility resources	4.5 6.0	3.5 4.5	3.0 4.0
(iv) assist in crowd control	4.5 6.0	3.5 4.5	3.0 4.0
(v) conduct or assist with humanitarian aid/disaster relief distribution	9.0 12.0	6.75 9.0	5.75 7.75
(vi) assist with policing operations as required and provide assistance to minimize looting	9.0 12.0	6.75 9.0	5.75 7.75
(vii) handover resources and responsibilities to civilian authority at closure	14.0 16.5	10.5 12.5	9.0 10.75

Table 2: Subject matter expert's information on collection and processing times (in hours) for tasks and options.

show how the performance varies as the number of personnel is reduced. Thus from the whole vignette and whole Operational Headquarters point-of-view, the performance can be increased by introducing the collaborative information environment while the number of personnel required in the headquarters can be reduced at the same time.

However, this new technology does not come without a cost, and it is necessary to estimate the life-cycle cost of the collaborative information environment along with the increased performance that can be obtained from its incorporation in the headquarters.

Number of Personnel	Status Quo	Option 1	Option 2
70	0.68	0.85	0.90
65		0.81	0.88
60		0.77	0.84
55		0.71	0.80
50			0.74
46			0.69

Table 3: Whole vignette (Operational Headquarters) performance (figure of merit) variation based on Operational Headquarters personnel levels.

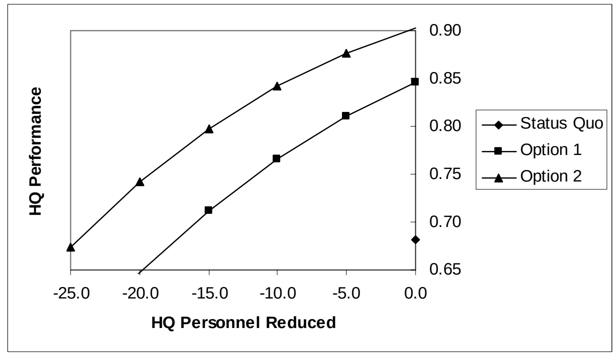

Figure 1: Relationship between whole vignette (Operational Headquarters) performance (figure of merit) and personnel level reductions.

3. The Cost Model - Formulation

The total average annual cost for the force development options was determined from the capital cost, the maintenance cost and the personnel cost. Average annual capital cost was determined by dividing the capital cost of communications and decision support technologies by the number of years they are expected to be in-service. This implicitly assumes that the technologies will be refreshed indefinitely to return to their original capability with periodic investment in capital. It was reasoned that technology degradation and obsolescence would increase rapidly with time, and an exponentially increasing maintenance cost model was adopted. Finally, personnel costs were calculated from the total number of Operational Headquarters personnel and their cost of employment. The average annual cost for a given force development option was then the sum of these three costs.

3.1 Average Annual Cost of Capital

The average annual cost of capital is fairly simple to calculate. One simply divides the initial capital cost by the years of life between refreshes. Both of these values are constant inputs to our model.

Let A be the initial capital cost of the communications systems and decision support applications in the force development option. Let L be the average actual life of the communications systems and decision support applications in the force development option. Then the average annual cost of capital will be

$$C_A = A / L .$$

3.2 Average Annual Cost of Maintenance

The maintenance cost model is somewhat more complex. First, it is assumed that the maintenance costs are exponentially increasing with the life of capability. Then the parameter of this exponential model is found based on the economic life model of the capability [7]. The economic life is an input to the model that assumes one knows the most efficient time to refresh the capability given the capital cost, that is, the time when the annual average cost of ownership is a minimum. However, for various reasons, the actual life of the capability may differ from the economic life. This actual life is also an input to the model. The annual average cost of maintenance is based on this actual life.

Let E be the average economic life of the communications systems or decision support applications in the force development option. The maintenance costs in year t of the life are assumed to be exponentially growing, that is

$$m(t) = \exp(\beta * t) .$$

Then the cumulative maintenance costs over T years of the life are

$$M(T) = \int_0^T m(t)dt = \int_0^T \exp(\beta * t)dt ,$$

The value of β is linked to the economic life, E, such that

$$(A + M(E)) / E$$

corresponds to a minimum value [7]. Thus when we know E, we can calculate β using a numerical approximation method and then the average annual cost of maintenance is simply

$$C_M = M(L) / L .$$

In Figure 2, the model of annual average costs of capital and maintenance are displayed based on varying the number of years between technology refreshes. In this graph, the economic life is 5 years. It corresponds to the minimum point of the upper curve, and is the sum total of the two lower curves. The monotonic decreasing curve shows how the average annual capital costs decrease as the years between refreshes increases. The monotonic increasing curve shows how the average annual cost of maintenance increases as the years between technology refreshes increases.

3.3 The Average Annual Cost of Personnel

The personnel are assigned optimally to data collection or information processing tasks in the functional decomposition of the scenario. To compute the annual cost of personnel, the total personnel assigned to the Operational Headquarters is multiplied by their individual personnel costs.

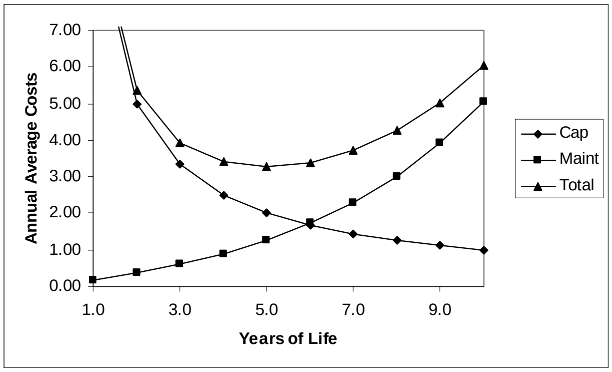

Figure 2: Model of annual average cost ($M/yr) based on economic life.

Let P be the number of personnel that are employed in the Operational Headquarters. Let α be the average annual cost of an individual person. Then the average annual cost of personnel is

$$C_P = \alpha * P .$$

3.4 The Average Annual Cost of the Force Development Options

In this study there are three force development options in terms of communication systems and decision support applications. However, with the collaborative information environment options, there is some flexibility in the number of personnel employed in the Operational Headquarters during the domestic humanitarian assistance disaster relief scenario. The number of personnel can be optimally determined based on maximizing the performance as calculated in the previous section for a given annual average cost calculated as

$$C = C_A + C_M + C_p .$$

Table 4 shows the annual average cost of these force development options. One can see that the annual average costs of capital vary between $0.68M/yr for the status quo and $2.12M/yr for option 2 while maintenance costs vary between $0.55M/yr and $1.63M/yr. These costs are dominated by the personnel cost which for all the options is $9.10M/yr. Therefore, a savings might be obtained if personnel can be reduced without reducing the performance.

4. Performance – Cost – Personnel Trade-offs for the Force Development Options

Table 5 provides a summary of the performance and cost trade-offs that can be obtained by including the collaborative information environment and reducing the number of personnel in the headquarters at the same time.

One can see from Table 5 that with the cost fixed at $10.3M/yr the collaborative

Costs	Status Quo	Option 1	Option 2
Capital	0.68	1.40	2.12
Maintenance	0.55	1.08	1.63
Personnel	9.10	9.10	9.10
Total	10.3	11.6	12.8

Table 4: Average annual costs for the force development options (in $M/yr) with 70 people in the Operational Headquarters.

Force Development Option	Number of Personnel	Average Annual Cost ($M/yr)	Performance (figure of merit)
Status Quo	70	10.3	0.68
Option 1	70	11.6	0.85
	65	10.9	0.81
	60	10.3	0.77
	55	9.6	0.71
	53	9.4	0.69
Option 2	70	12.8	0.90
	65	12.2	0.88
	60	11.5	0.84
	55	10.9	0.80
	50	10.2	0.74
	46	9.7	0.69

Table 5: Average annual cost ($M/yr) and performance (figure of merit) trade-offs for the various force development options.

information environment in option 1 can produce an increase in performance to 0.77 (compared to 0.68 for the status quo option) while reducing the number of personnel in the headquarters to 60. Similarly, by introducing the collaborative information environment with a secure wireless broadband network in option 2, the performance can be increased to 0.74 while reducing the number of personnel in the headquarters to 50, keeping the cost approximately the same at $10.2M/yr.

Furthermore, the annual average cost can be reduced to approximately $9.4M/yr without reducing performance by adding the collaborative information environment in option 1 and reducing the personnel at the same time to 53 people, or to $9.7M/yr by introducing the collaborative information environment with secure wireless broadband network in option 2 while at the same time reducing the number of personnel in the headquarters to 46 people.

5. Schedule and Risk Models

The schedule and risk models are computed based on project management characteristics of the project and therefore are not directly related to the operational considerations of performance and personnel. They are simply provided to the decision-makers as information concerning viability of the technological projects. In particular, the schedule model attempts to estimate the time to implement the project with all of its components. The risk model attempts to place a probability or confidence in meeting the performance, cost, and schedule targets based on the maturity of the technologies involved in the solution. These two estimates, schedule and risk, are provided along with the information of the force development options of performance, cost and people which allow for tradeoffs to be made.

5.1 The Schedule Model

The schedule model is used to calculate the time required to implement a force development option. It is assumed that the capability is currently available in the status quo option, so the time to implement in this case is zero.

The schedule model applies to the future capabilities introduced through the collaborative information environment and the secure broadband wireless network, and will be based on the technology readiness level [8] of these capabilities as an input to the model. The technology readiness level is a value between 1 and 9. A value of 1 implies the technology is currently in a basic research stage and is assumed to be 20 years or more from implementation. A technology readiness level of 9 means that the capability has been field tested under real-life conditions and is assumed to be less than a year from implementation. For the sake of the schedule model, it was assumed that the systems in the status quo option have a technology readiness level of 10 and that the relationship between the technology readiness level and the time to implement the technology was an exponentially decreasing curve between 20 for technology readiness level 1 and 0 for technology readiness level 10 (see Figure 3).

It was assumed that the collaborative information environment has a technology readiness level of 7 and therefore the time to implement was 2 years. Furthermore, it was assumed that the technology readiness level of the secure broadband wireless network was 4. Since option 2 involves the introduction of both the collaborative information environment and the secure broadband wireless network, these capabilities were

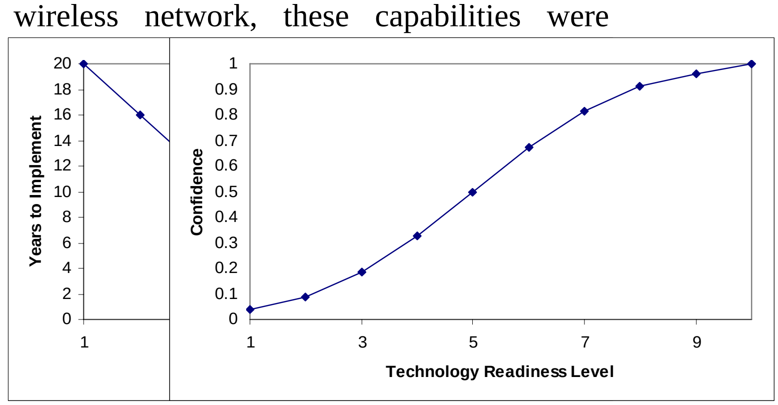

Figure 3: A model of the relationship between technology readiness level and years to implement the technology.

5.2 The Risk Model

The risk model attempts to model the confidence that one has that the force development option will be able to meet the performance requirements, within the cost and schedule estimates. This is similar to the reliability of the numerical estimates. It applies only to future capabilities and is also based on the technology readiness level of the capability.

It is assumed that the confidence or reliability associated with the estimates of the performance, cost, schedule and risk in the capabilities within the status quo option is 1.0 (all the capabilities in this option are assumed to have a technology readiness level of 10). It is assumed that the confidence that one has in future capabilities is an S-shaped curve the increases between 0 and 1 with the technology readiness level (see Figure 4).

Then based on the confidence one has in each of the capabilities in the force development option, one can calculate the confidence that one has in the total force development option using a reliability paradigm; namely, by multiplying these individual confidence values together. That is, if one of the capabilities fails to perform on schedule and within cost, the whole force development option will fail to perform on schedule and within cost. Therefore, the risk associated with the force development option is simply 1 minus the product of the confidence levels for each of the capabilities involved in the option. Its values will range from 0 (complete confidence in each capability) to 1 (zero confidence in one or more of the force development option's capabilities).

Figure 4: A model of confidence in a technology based on the technology readiness level.

Based on these assumptions, the risk (i.e. serious performance problems, cost overruns, or schedule delays) associated with the collaborative information environment (option 1) was estimated to be 0.19, whereas the risk associated with the collaborative information environment combined with a secure broadband wireless network (option 2) was 0.73.

The schedule and risk estimates were based on the technologies associated with the force development options and only represent the project management information that can be provided to decision-makers along with the cost and performance estimates. It does not consider the operational timings and risks associated with the employment of these options in this humanitarian assistance disaster relief scenario.

6. Capability Engineering Decision Framework – Final Results

The goal of the capability engineering process in the Canadian Forces is to place viable force development options in front of decision-makers to fill the gaps found in the capability-based planning process. The capability engineering team is charged with this responsibility. As part of the capability engineering team, operational research analysts develop a capability engineering decision framework consisting of quantitative models of performance, cost, schedule and risk. These models are supported with data provided by operational subject matter experts on the capability engineering team.

The final result might be similar to that shown in Table 6 which quantifies the performance, cost, schedule and risk associated with the status quo option compared to two other technological options which have numerous sub-options based on various personnel establishments.

The results in Table 6 demonstrate that by introducing new technology and wisely reducing personnel one can improve performance at the same annual cost with a few years of development time and within reasonable levels of risk.

7. Conclusions

Quantitative models were built to measure performance based on a figure of merit related to decision quality, and cost based on the average annual cost of ownership in terms of capital, maintenance and personnel. Schedule (in terms of years to implement the force development option) and risk (of not meeting the performance, cost and schedule estimates) were calculated based on the technology readiness level. These four dimensions of a force development option represent the fundamental elements of a business case. Performance, cost, schedule and risk models were prescribed in the capability engineering process as part of the duties of the operational research analysts in their development of a capability engineering decision framework.

The scenario was decomposed into vignettes, tasks and functions and estimates of the personnel time to complete the functions were provided by a subject matter expert. These could then be employed in a performance model for command and control based of the requirements to orient, evaluate, decide and implement decisions at the Operational Headquarters when augmented by hardware and software from various technological options.

Force Development Option	Status Quo	Option 1			Option 2			
Number of Personnel	70	70	60	53	70	60	50	46
Performance (figure of merit)	0.68	0.85	0.77	0.69	0.90	0.84	0.74	0.69
Average Annual Cost ($M/yr)	10.3	11.6	10.3	9.4	12.8	11.5	10.2	9.7
Schedule (years to implement)	0	2	2	2	9	9	9	9
Risk (1–reliability)	0	0.19	0.19	0.19	0.73	0.73	0.73	0.73

Table 6: Example results for each of the force development options using specified sets of technologies. The number of Operational Headquarters personnel was varied while the compliment of technologies for an option remained fixed. (Typical variations in the number of personnel have negligible impact on technologies and technology-related costs.) The status quo option involves a hardware and software refresh of the current systems used in Command and Control at the operational level, option 1 involves an investment in hardware and software to develop a collaborative information environment at the Operational Headquarters, and option 2 involves an investment in hardware and software to develop a wireless broadband network to move the collaborative information environment to the tactical level.

The cost model was based on the economic life concept from engineering management. In this case, the annual average costs of the force development options were dominated by personnel costs. Therefore, by introducing technology and reducing personnel requirements at the same time, performance could be improved and total costs reduced at the same time.

The scenario was decomposed into vignettes, tasks and functions by the operational subject matter experts. Then technological options were developed by the technological subject matter experts. Quantitative models for performance, cost, schedule and risk were developed by the operational research analysts and the data to support these models was provided by the operational and technological subject matter experts. This demonstrates the benefits of the capability engineering process that combines the talents of operational and technological subject matter experts with those of operational research analysts. Furthermore, it demonstrates the benefits of quantitative modeling to help maximize the benefits and minimize the costs associated with introducing new technology for Command and Control in complex environments.

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