# Schedule Risk Analysis of Capability Development Initiative Portfolios

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## ABSTRACT

*In order to fulfill their mandate, armed forces require an extensive suite of capabilities, the development of which involves a large number of interrelated capability development initiatives. The network of dependencies between initiatives is often quite complex. Therefore, changes, delays and cancellations in any one of them can have significant first and second order impact throughout the capability development initiative portfolio. It is important to identify such potential impact as early as possible in the decision process to allow for timely mitigation. Defence Research and Development Canada's Centre for Operational Research and Analysis developed, for the Canadian Army, a prototype schedule risk analysis tool to support this task. Based on estimates of activity duration provided by subject matter experts, the tool uses a Monte Carlo simulation to forecast when high-level activities involved in capability development initiatives may be expected to start and end—taking into account dependencies between initiatives and flagging the impact of potential delays on readiness. This paper describes the prototype and reports on lessons learned during its development, notably with respect to the minimization of data requirements and the challenges involved in presenting results of the schedule risk analysis to decision makers.*

## 1.0 INTRODUCTION

In order to fulfill their mandate, armed forces require an extensive suite of capabilities,[1] the development of which involves a large number of interrelated Capability Development Initiatives (CDIs). Changes, delays and cancellations in any one of these CDIs can have significant first and second order impact throughout the CDI portfolio (CDIP), especially given that the network of dependencies between them can be quite complex. It is important to determine such potential impact as early as possible in the decision process to allow for timely mitigation. The process of performing this determination is part of what is known in project management as risk analysis. (As mentioned in the final report [2] of the NATO Research Task Group SAS-109 on Risk Analysis for Acquisition Programs, risk analysis may in general consider cost, schedule and performance risks.) As a first step in helping the Canadian Army (CA) streamline how it does such risk analysis at the Army CDIP (ACDIP) level, the Defence Research and Development Canada (DRDC) Centre for Operational Research and Analysis (CORA) developed a prototype tool to look specifically at schedule risk. The tool, the subject of this paper, is named ACDIP Visualization and Analysis (AVA) and leverages a Monte Carlo simulation in order to assess schedule risk.

Section 2 describes the model behind AVA, while section 3 presents sample output from the prototype. Section 4 discusses lessons learned from its development and provides recommendations for future work. Section 5 contains concluding remarks. The information presented in this paper was extracted from a more detailed

[1] A capability is defined in NATO as "the ability to create an effect through employment of an integrated set of aspects categorized as doctrine, organization, training, materiel, leadership development, personnel, facilities, and interoperability" [1].

document submitted for publication as a DRDC scientific report, and the figures contained herein were taken or adapted from it [3].

## 2.0 AVA MODEL

In their request for the development of a schedule risk analysis tool for the ACDIP, the CA had two main requirements:

- The tool should focus on determining the impact of potential CDI delays on the readiness of the CA to deliver on their assigned tasks; and
- The tool should require as little data as possible in order to limit the level of effort required to collect and update it.

The first step in the development of AVA was thus the determination of a high-level model that relates the ACDIP to assigned tasks. The resulting model is shown in Figure 2-1.

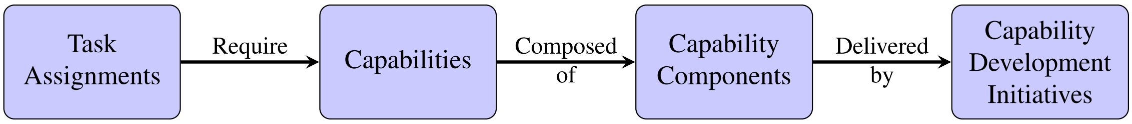



**Figure 2-1: ACDIP representation in AVA.**

Task assignments are characterized in AVA by the military unit to which they are assigned and the time period of the assignment. They require certain capabilities, each composed of various capability components that may include equipment, training, doctrine or any other element mentioned in the definition of *capability* in footnote 1. In turn, these capability components are delivered by CDIs. AVA aims to determine the probability that these CDIs will deliver the capability components in time for the military units to have the capabilities required for their task assignments. In order to perform this assessment, AVA requires a high-level representation of the work plan for each applicable CDI: the sequence of high-level steps, with possible branches and merges, that describes what the CDI must do in order to deliver the relevant capability components.

In mathematical terms, such a sequence of steps is called a Directed Acyclic Graph (DAG), a graph being an abstract representation of pairwise relationships among a group of entities [4]. (In graph theory, each such entity is called a node or vertex and each relationship is known as an edge.) The graph for a CDI work plan is said to be directed because each edge has a direction that indicates that a given node comes before another one. It is said to be acyclic because following the sequence of edges must never lead from any given node to itself; otherwise, the corresponding step of the work plan would need to be done before it could start—which would be contradictory. So in AVA, the work plan for a CDI is captured by a DAG that represents its high-level steps, including the delivery of capability components. It doesn't stop there however. The DAG also captures the capabilities that become available once the required capability components are delivered, and the task assignments that are enabled by these capabilities. Furthermore, steps in CDIs may depend on steps of other CDIs, and AVA uses a single DAG to represent the entire ACDIP—from capability development initiatives to task assignments.

An important characteristic of DAGs is that one can always find at least one topological order, which is a linear ordering of the nodes such that all edges originating from any given node point to nodes that appear later in the list. This significantly simplifies calculations, since many quantities of interest can be calculated by considering each node one at a time and only once, either in topological order or in reverse topological order. For instance, the start date of each CDI step can only depend on steps that appear earlier in the topological order. It can thus be calculated simply by walking the topological order in the forward direction.

Besides the relationship between CDI steps, the other main piece of data required to perform a schedule risk analysis is an estimate of the duration of each step. Since the actual duration can in general be known only after the fact, it is characterized in the work plan by a probability distribution—the beta, normal, uniform and triangular distributions being the most widely used [5]. In 2008, the Association for the Advancement of Cost Engineering (AACE) recommended the use of another probability distribution: the double-triangular distribution, which is composed of two triangular distributions side-by-side [6]. The advantage of the new distribution compared to the four mentioned above is that the ratio of the probability of overrun to the probability of underrun can be set independently of the other distribution parameters, with overrun and underrun being respectively defined as taking more time or less time than the most likely duration. In addition to this ratio, the double-triangular distribution also requires the specification of the minimum duration, maximum duration and most likely duration. The AVA prototype uses a discrete version of the double-triangular distribution recommended by the AACE, because step duration is modelled as an integer quantity (number of weeks). Figure 2-2 shows an example of probability mass function for this distribution. In this specific example, the probability of overrun, the probability of underrun and the probability of having the most likely value are all equal to 1/3. A regular integer triangular distribution with the same bounds and most likely value would have a fatter tail on the right than the left and the probability of overrun would necessarily be greater than the probability of underrun.

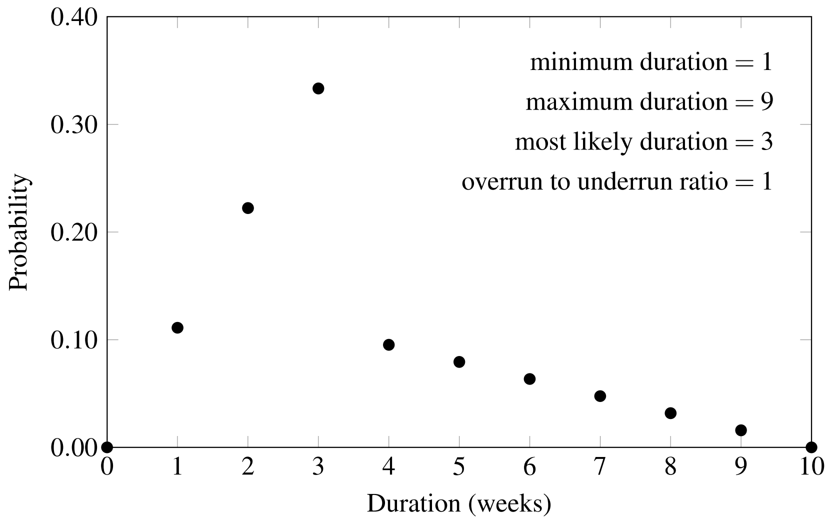



**Figure 2-2: Sample probability mass function of integer double-triangular distribution.**

Equipped with the ACDIP DAG and the parameters of the integer double-triangular distribution for each CDI step, AVA performs a Monte Carlo simulation to assess the risk associated with the scheduling of the ACDIP. First, for each Monte Carlo sample, AVA performs the following calculations:

- Determine a fixed step duration for each CDI step by sampling the corresponding integer double-triangular distribution;
- Go through the ACDIP DAG in topological order and calculate the start and end dates of each step based on its duration and on its step dependencies;
- Go through the ACDIP DAG in reverse topological order and calculate the dates by which each step must start and end (the cut-off start and end dates) based on its duration and on the cut-off requirements of the steps that depend on it; and
- Compare the results of the previous two steps to determine which cut-off requirements are met and which are not.

Then, AVA compiles the results from all the Monte Carlo samples as follows:

- Calculate the median start and end dates of each CDI step, with percentile-based error bars, and the probability that each cut-off requirement will be met; and
- Calculate the probability that each step dependency will be on the critical path.[2]

From these results, AVA can estimate the delivery dates of the capability components, the availability dates of the capabilities and the dates by which the task assignments will have all their capability requirements fulfilled, as well as the probability that the corresponding cut-off dates will be met. It can also determine the stochastic critical path through the entire DAG. This depiction of the schedule risk can help the decision maker assess the impact of delays or changes on the ACDIP and determine appropriate mitigation measures proactively for the highest risk areas.

# 3.0 SAMPLE OUTPUT

The AVA prototype was developed in Microsoft Access, supplemented by Graphviz [7]. It produces two main types of report: an interactive high-level report and a more detailed work plan chart, respectively produced by Microsoft Access and Graphviz and described in sections 3.1 and 3.2.

## 3.1 Interactive High-Level Report

The interactive high-level report lists the CDIs that have a higher or unknown probability of not delivering on time: those for which the probability is higher than a user-defined high-risk threshold are highlighted in red; those for which the probability cannot be calculated because of missing data are highlighted in orange; those that are lower than the high-risk threshold but higher than a user-defined medium-risk threshold are highlighted in yellow; and the other ones are omitted. For each CDI displayed, the report shows the capability components and task assignments that would be impacted by the late delivery. It allows the user to dig down into the CDI hierarchy[3] in order to see the predicted start and end dates of the CDI steps, as well as their predicted cut-off dates. It also shows cross-CDI step dependencies that are on the stochastic critical path, but it cannot display the stochastic critical path in its entirety because of the linear nature of the textual report. Doing so requires using a graphical representation, such as the work plan chart described in the next section.

## 3.2 Work Plan Chart

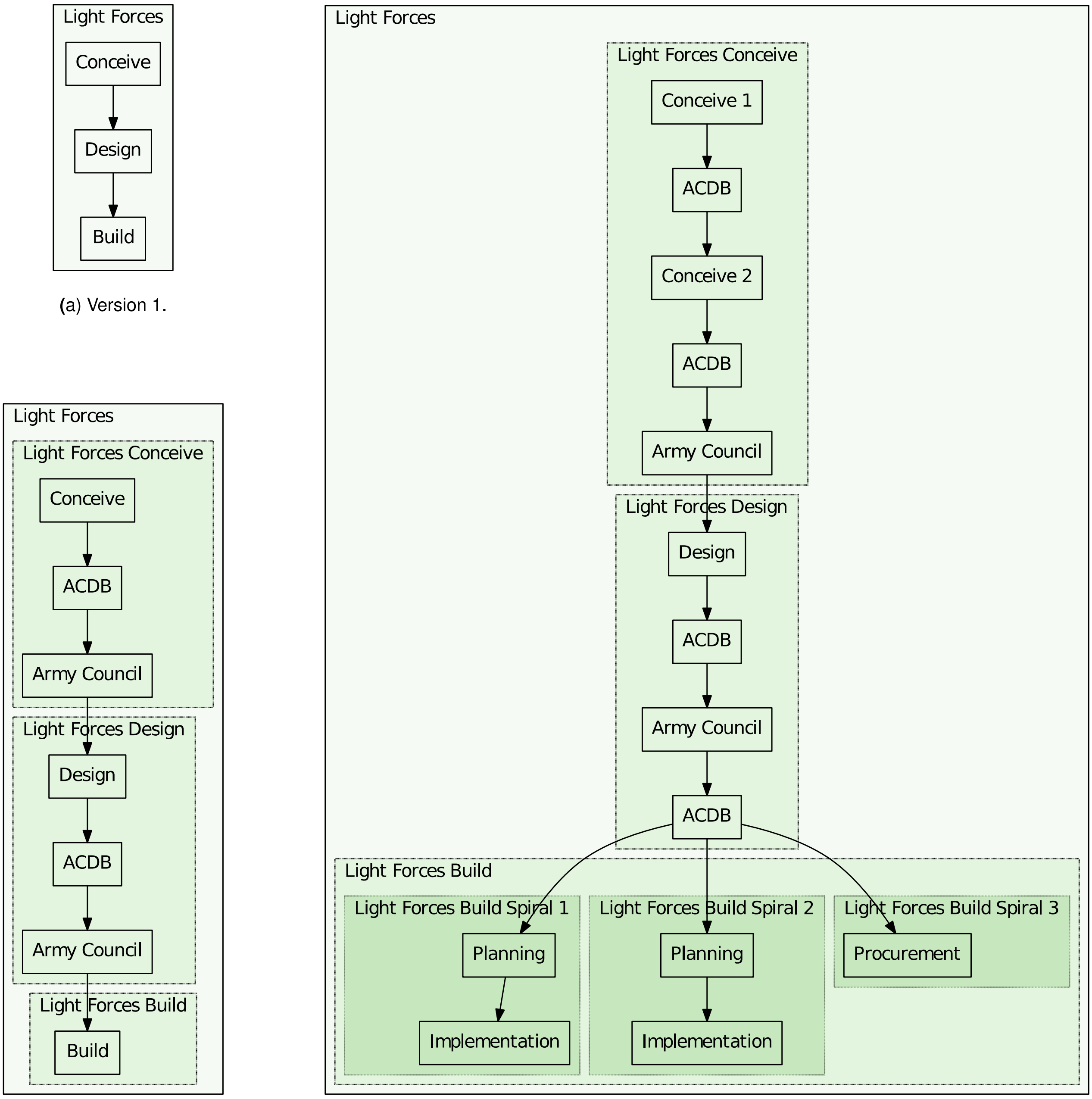
The work plan chart is a flowchart that displays the dependencies between the steps involved in a CDI. An example of how the work plan chart could have evolved over time for the CA Light Forces CDI, had AVA been used for its management, are shown in Figure 3-1. Initially, the work plan could have been very high-level with only three steps: Conceive, Design and Build, the first three pillars of the CA capability development process.[4] This is shown in Figure 3-1(a). As more information about the work plan became available, it might have been helpful to create sub-CDIs for each of the Conceive, Design and Build phases and to add steps in each of them to model the fact that approval of the Army Capability Development Board (ACDB) and of the Army Council would be sought before moving from one phase to the next. This second version is shown in Figure 3-1(b). When ACDB requested some changes to the concepts developed initially and required that its approval be sought again before moving on to the Design phase, a second Conceive step and a second ACDB

[2] In a deterministic critical path analysis, each edge of the work plan is either on the critical path or not. In a stochastic schedule risk analysis, each edge has a certain probability of being on the critical path—as the actual critical path will vary depending on how the work plan ends up unfolding.

[3] Each CDI can be composed of sub-CDIs, as shown in the examples below.

[4] The fourth pillar, Manage, applies to the usage of capabilities rather than their development.

step could have been added to the Conceive sub-CDI of the work plan, as shown in Figure 3.1(c). Finally, once the decision was made to use a spiral approach for the Build phase, three sub-CDIs could have been added to it — also shown in Figure 3-1(c). It doesn't stop there however: more details about the work plan could continue to be added as needed in order to have a more precise depiction of the CDI schedule, always avoiding unnecessary details in order to reduce data requirements.




(a) Version 1.

(b) Version 2.

(c) Version 3.

**Figure 3-1: Sample iterative work plan for Light Forces CDI.**

An example of what a more detailed build phase might look like is shown in Figure 3-2 using old (and thus obsolete) data collected from the CA's Tactical Armoured Patrol Vehicle (TAPV) project. Figure 3-2 contains a lot of information, but we will highlight only a few points. First, while Figure 3-1 only showed steps and dependencies, Figure 3-2 also shows the risk levels and stochastic critical path calculated by AVA: steps highlighted in yellow have a medium risk of not meeting their cut-off dates, while those in green have a low risk; and arrows drawn in black indicate dependencies that are on the stochastic critical path, while those in grey represent those that are not on it. AVA can also write for each step the estimated start and end dates as well as their cut-off values, but they make the chart even busier and were omitted here. However, the main point of showing Figure 3-2 is to illustrate how quickly the work plan chart becomes overwhelming as the work plan size increases and how displaying it in its entirety may be of limited value. It is certainly possible to analyze the chart carefully in order to determine which sequence of steps is leading to an increased risk, but it would be a lot easier if unrelated information was omitted. While the AVA prototype cannot do that automatically, the result of a similar manual trimming is shown in Figure 3-3(a).

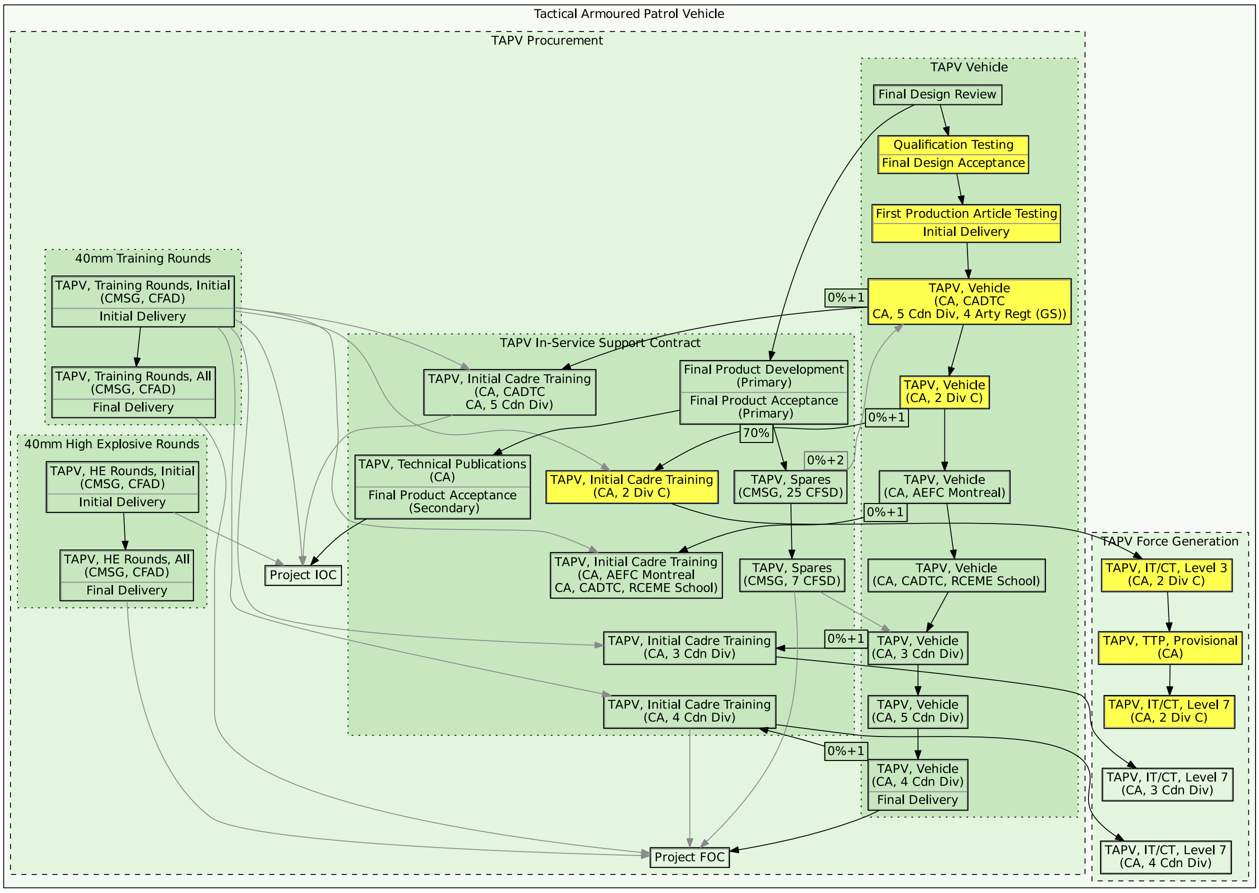
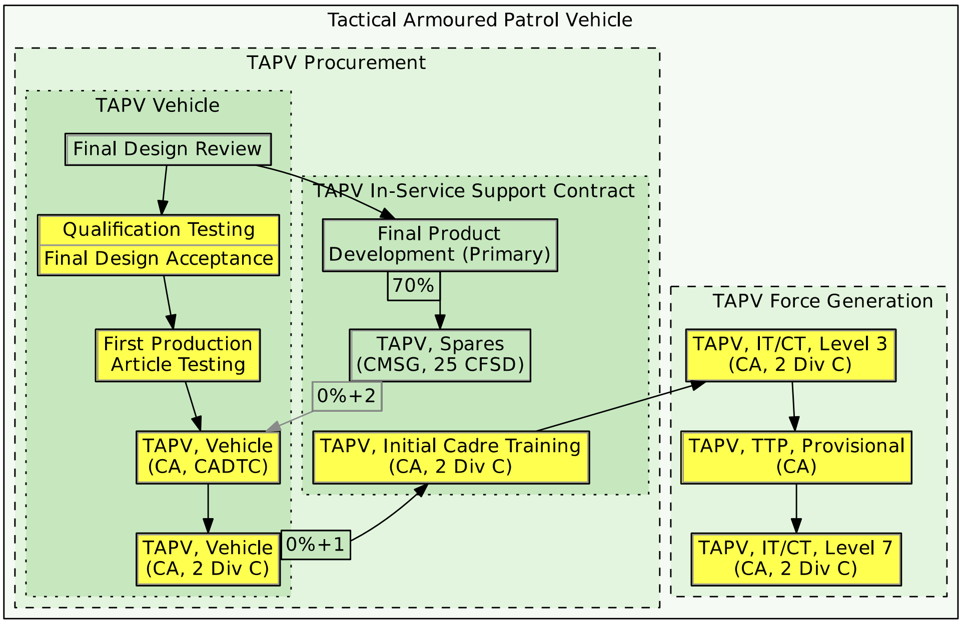



**Figure 3-2: Sample iterative work plan for Light Forces CDI.**

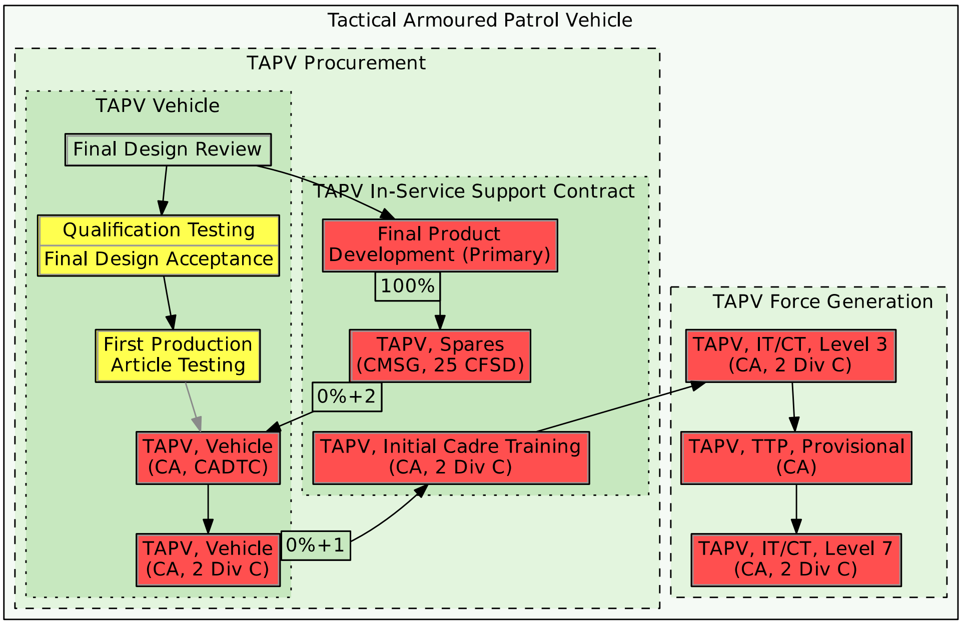
Figure 3-3(a) is much easier to read than Figure 3-2 although it conveys as much information about the stochastic critical path, because it displays only relevant information. One thing to note is that the delivery of spares to 25 CFSD can start once the support documents developed as part of the In-Service Support Contract have been completed at 70% (indicated by the 70% label beside the arrow representing that dependency[5]). In

[5] Similarly, the 0%+1 and 0%+2 labels indicate that the following step can start respectively 1 or 2 weeks after the previous step has started.

an earlier version of the work plan, shown in Figure 3-3(b), this was assumed to be 100%, which led to a high risk of delay.




(a) Baseline scenario.




(b) Alternate scenario.

**Figure 3-3: Critical subset of sample iterative work plan for Light Forces CDI.**[6]

[6] Figure 3-3 contains several acronyms that are not defined in the text: CADTC = Canadian Army Doctrine and Training Centre, 2 Div C = 2e Division du Canada, CMSG = Canadian Material Support Group, 25 CFSD = 25 Canadian Forces Supply Depot, IT/CT = Individual Training/Collective Training, and TTP = Tactics, Techniques and Procedures.

# 4.0 LESSONS LEARNED

## 4.1 Minimization of Data Requirements

When doing schedule risk analysis, it may be tempting to develop detailed work plans in order to have steps for which the duration is easy to estimate. However, that can lead to a data maintenance nightmare, as the collection and update of the data may end up taking an inordinate amount of time and effort. If the level of effort is too high, it can act as a significant deterrent to performing a formal schedule risk analysis—which is counterproductive given the important role that it can play in planning for the unknown. It is likely better to start with high-level work plans that focus on the main milestones, as illustrated in Figure 3-1, and to include only the level of detail required in order to capture the important relationships between CDIs.

## 4.2 Accuracy of Duration Estimates

Irrespective of the level of detail of the work plan, the validity of the schedule risk analysis depends on the accuracy of the data—in particular the accuracy of the step duration estimates. It can be tempting to reverse-engineer the official plan when providing data for a schedule risk analysis, and that was sometimes observed when collecting data for this work. However, duration estimates must be based on expert judgment rather than official numbers in order for the exercise to be useful. In order for a schedule risk analysis program to succeed, it is important for the chain of command to support it by nurturing an environment where subject matter experts are encouraged to provide accurate estimates even when it contradicts the official plan.

## 4.3 Displaying Results

On the one hand, military officers liked the interactive nature of the high-level report and the fact that it summarizes the main areas of risk. On the other hand, they found that the lack of a linear timeline in the work plan chart made it difficult to interpret and that it quickly became unwieldy as the level of detail increased. Given that the work plan chart is the most concise and clear way of displaying the relationships in the work plan, it may be worth exploring ways to make it more palatable to the client, such as:

- Devising an algorithm that would, when displaying critical paths, omit automatically the steps that are not related to them in order to reduce visual overload and focus the attention on the important information; and
- Offering the option of laying out the steps of the work plan along a linear timeline.

# 4.0 CONCLUSION

DRDC CORA developed the AVA prototype to help the CA determine how it could improve the performance of schedule risk analysis for its CDI portfolio. The tool, based on Monte Carlo simulations, estimates when capabilities can be expected to become available and calculates the probability that the capability requirements of task assignments will be met on time. It reports the results of its calculations using two main reports: an interactive textual report that highlights the main areas of risk and a work plan chart that displays the stochastic critical paths in the work plan in order to help identify which parts contribute to the increased risk of delay. The exploratory work done with AVA helped identify three main lessons that should be kept in mind when developing a production schedule risk analysis tool. First, it is important to keep a high-level view when modelling the work plan in order to reduce data requirements. Second, the subject matter experts must be empowered to provide accurate duration estimates even when they differ from the official plan. Finally, while a flowchart is the most concise way to display the step relationships in a work plan, it was perceived by the client as non-intuitive and improvements would be needed in order to simplify its interpretation.

## 5.0 REFERENCES

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