Vignette, Task, Requirement, and Option (VITRO) Analyses Approach

Application to Concept Development for Domestic Chemical, Biological, Radiological, and Nuclear (CBRN) Event Response

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DRDC Centre for Operational Research & Analysis

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IMPORTANT INFORMATIVE STATEMENTS

Abstract

Using notional data, we describe a systematic, transparent, and generic planning approach that is based on sequential Vignette, Task, Requirement, and Option (VITRO) analyses. Whereas vignette analysis yields likelihood estimates for potential events of interest, task analysis gauges probabilities for tasks that the Canadian Armed Forces (CAF) may be requested to perform in response to such events. Next, requirement analysis produces estimates of what the CAF would need to perform such tasks adequately, across the vignette set. Finally, option analysis aggregates the three foregoing analyses' results, to assess potential force packages' performance versus a range of prospective tasks. The high-level, quantitative results readily enable decision makers to weigh possible trade-offs between resourcing options and consequent force package capabilities. The VITRO approach has been applied to support the development of a CAF concept for domestic Chemical, Biological, Radiological, or Nuclear (CBRN) event response. Though the approach is generic, we have also used a domestic CBRN event response context to frame this report's notional examples.

Résumé

À l'aide de données fictives, nous décrivons une méthode de planification systématique, transparente et générique fondée sur une succession d'analyses (situations, tâches, besoins, et options - VITRO). Alors que l'analyse de situations estime les probabilités que certains événements surviennent, l'analyse de tâches estime leurs probabilités d'exécution par les Forces armées canadiennes (FAC) si les événements considérés se produisaient. Ensuite, l'analyse des besoins estime ce qu'il faudrait aux FAC pour exécuter ces tâches adéquatement, pour l'ensemble des situations. Enfin, l'analyse d'options regroupe les résultats des trois analyses précédentes, pour évaluer le rendement des ensembles de forces possibles par rapport à une gamme de tâches prospectives. Les résultats quantitatifs de haut niveau permettent facilement aux preneurs de décision de juger des compromis possibles entre les options en matière de ressources et les capacités des ensembles de forces qui en découlent. On a appliqué la méthode VITRO pour appuyer le développement d'un concept des FAC concernant l'intervention à la suite d'un événement chimique, biologique, radiologique ou nucléaire (CBRN) sur le territoire national. Bien qu'il s'agisse d'une méthode générique, nous nous sommes également servis du contexte de l'intervention à la suite d'un événement CBRN pour situer les exemples fictifs du présent rapport.

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Executive summary

Vignette, Task, Requirement, and Option (VITRO) Analyses Approach: Application to Concept Development for Domestic Chemical, Biological, Radiological, and Nuclear Event Response

P.W. Dooley; Y. Gauthier; DRDC TR 2013-255; Defence R&D Canada – Centre for Operational Research & Analysis; December 2013.

Introduction: To position itself for success, an organization must effectively anticipate and prepare for the conditions in which it will operate. However, doing so can be challenging. For instance, effective planning requires sound projections concerning the spectrum of potential operating conditions, their probabilities of occurrence, the range of an organization's potential tasks, the likelihoods of performing such tasks, the resource requirements associated with satisfactory task performance, the availability of these resources to the organization, and many other factors.

To address these planning issues, we describe (using notional data) a systematic, transparent, and generic approach that is based on sequential Vignette, Task, Requirement, and Option (VITRO) analyses. Whereas vignette analysis yields likelihood estimates for potential events of interest, task analysis gauges probabilities for tasks that the Canadian Armed Forces (CAF) may be requested to perform in response to such events. Next, requirement analysis produces estimates of what the CAF would need to perform such tasks adequately, across the vignette set. Finally, option analysis aggregates the three foregoing analyses' results, to assess potential force packages' performance versus a range of prospective tasks.

Results: The VITRO approach yields high-level, quantitative results, which are represented using succinct yet informative visualization schemes. These attributes readily enable decision makers to weigh possible trade-offs between resourcing options and consequent force package capabilities.

Significance: The VITRO approach is broadly applicable and provides systematic, transparent, and quantitative means for identifying, eliciting, and aggregating key planning factors. By deconstructing complex planning problems into sequential analyses, the approach enhances planning rigour and improves decision support. For instance, its first real-world application successfully informed the development of a CAF concept for domestic Chemical, Biological, Radiological, or Nuclear (CBRN) event response.

Future plans: The VITRO approach's first use generated interest from other CAF organizations and elsewhere within the Government of Canada. Though discussions continue, future applications may include supporting CAF concept development for responding to CBRN events abroad, evaluating potential courses of action during contingency planning for CBRN event response (whether domestic or expeditionary), and uses in areas unrelated to CBRN defence planning. Moreover, since the four constituent analyses are modular, each may be applied in isolation or in conjunction with other methods. For instance, the incorporation of the vignette analysis method into a risk assessment approach for CBRN defence purposes is being explored.

Sommaire

Vignette, Task, Requirement, and Option (VITRO) Analyses Approach: Application to Concept Development for Domestic Chemical, Biological, Radiological, and Nuclear Event Response

P.W. Dooley; Y. Gauthier; DRDC TR 2013-255; R & D pour la défense Canada – Centre d'analyse et de recherché opérationelle; Décembre 2013.

Introduction: Pour être en mesure de réussir, une organisation doit correctement anticiper les conditions dans lesquelles elle fonctionnera et elle doit s'y préparer. Cependant, cela peut être une tâche difficile. Par exemple, pour bien planifier, il faut faire de solides prévisions concernant la gamme de conditions d'opération possibles, la probabilité qu'elles se produisent, la portée des tâches possibles d'une organisation, la probabilité d'exécuter ces tâches, les besoins en ressources nécessaires pour le bon accomplissement des tâches, la possibilité pour l'organisation de se procurer ces ressources, et bien d'autres facteurs.

Pour trouver une solution à ces problèmes de planification, nous décrivons (en se servant de données fictives) une méthode de planification systématique, transparente et générique fondée sur une succession d'analyses (situations, tâches, besoins, et options - VITRO). Alors que l'analyse de situations estime les probabilités que certains événements surviennent, l'analyse de tâches estime leurs probabilités d'exécution par les Forces armées canadiennes (FAC) si les événements considérés se produisaient. Ensuite, l'analyse des besoins estime ce qu'il faut aux FAC pour exécuter ces tâches adéquatement, pour l'ensemble des situations. Enfin, l'analyse d'options regroupe les résultats des trois analyses précédentes, pour évaluer le rendement des ensembles de forces possibles par rapport à une gamme de tâches prospectives.

Résultats: La méthode VITRO donne des résultats quantitatifs de haut niveau, que l'on représente à l'aide de schémas simples mais informatifs. Ceux-ci permettent facilement aux preneurs de décision de juger des compromis possibles entre les options en matière de ressources et les capacités des ensembles de forces qui en découlent.

Importance: La méthode VITRO peut être appliquée de manière générale et elle offre un moyen systématique, transparent et quantitatif pour identifier, obtenir et regrouper les principaux facteurs de planification. En soumettant des problèmes complexes de planification à des analyses consécutives, la méthode renforce la rigueur de la planification et améliore l'appui aux décisions. Par exemple, sa première application réelle a permis d'obtenir de l'information à l'appui du développement d'un concept des FAC concernant l'intervention à la suite d'un événement chimique, biologique, radiologique ou nucléaire (CBRN) sur le territoire national.

Plans futurs: La première utilisation de la méthode VITRO a suscité l'intérêt d'autres organisations, dans les FAC et ailleurs dans l'administration canadienne. Bien que les discussions se poursuivent, les futures applications pourraient inclure l'appui du développement d'un concept des FAC pour intervenir à la suite d'événements CBRN à l'étranger, l'évaluation des plans d'action possibles pendant la planification d'urgence d'une intervention à la suite d'un événement CBRN (que ce soit sur le territoire national ou en mode expéditionnaire), et des

utilisations dans des domaines sans relation avec la planification de la défense CBRN. De plus, étant donné que les quatre analyses qui constituent la méthode sont modulaires, chacune d'entre elles peut être utilisée seule ou avec d'autres méthodes. Par exemple, on est en train d'étudier l'ajout de l'analyse de situations à une méthode d'évaluation du risque à des fins de défense CBRN.

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We have also benefited from the knowledge contributed during real-world data elicitation workshops by CBRN advisors and other specialists from Canada Command; Canadian Joint Operations Command; Canadian Special Operations Forces Command; the Canadian Army; the Royal Canadian Air Force; the Royal Canadian Navy; the Directorate of Chemical, Biological, Radiological and Nuclear Defence and Operational Support; the Canadian Forces Health Services; and the Strategic Joint Staff.

Finally, we gratefully acknowledge helpful, early discussions with Mr. David Shaw of DRDC CORA.

1 Introduction

1.1 Operational planning challenges

To position itself for success, an organization must effectively anticipate and prepare for the conditions in which it will operate. However, doing so can be challenging. For instance, effective planning requires sound projections concerning the spectrum of potential operating conditions, their probabilities of occurrence, the range of an organization's potential tasks, the likelihoods of performing such tasks, the resource requirements associated with satisfactory task performance, the availability of these resources to the organization, and many other factors.

Such projections can be difficult to formulate and apply. Several factors may complicate planning efforts further, such as:

- An organization's knowledge of its current operating environment may be imperfect.
- An organization's future operating environment may be highly uncertain. Moreover, future operating conditions may be historically rare or unprecedented.
- Requisite information may be diverse and might reside outside an organization.
- Subjective judgements may be necessary.
- Information may be recorded or communicated ambiguously, thereby inhibiting common understanding among planners.
- In a hierarchical organization, certain planning decisions are taken ultimately by executives. In such settings, detailed information residing at the working level must be aggregated to facilitate senior-level decision making. The aggregation process should employ logically valid and transparent means, to preserve its fidelity and to enable an examination of the basis on which a decision will be or has been made.

Using rigorous approaches, it is possible to reduce a planning problem's complexity and increase the quality of (and confidence in) a resulting course of action. Absent a rigorous approach, planning may be predicated on conflicting subjective and/or unsubstantiated opinions, which may not be aggregated properly, and may yield flawed plans. Such circumstances may give rise to misunderstandings or controversies that can delay or derail planning efforts. Moreover, if planners' assumptions, analyses, or conclusions are unsatisfactory to a decision maker, additional planning rounds may be required, or the plan(s) may be rejected altogether.

To enhance rigour and reduce complexity, operational analyses can be conducted to inform every stage of an organization's planning process. For instance, they can:

- help planners clearly define the nature and scope of a planning problem and identify relevant factors,

- propose systematic approaches for producing planning projections,
- facilitate the collection of necessary and unambiguous data via means that reduce or eliminate potential biases,
- develop and apply valid and transparent methods for aggregating diverse data, and
- provide interpretations and visualizations of the data to inform decision making.

1.2 Development of CJOC's concept of operations for responding to domestic CBRN events

In 2012, Canada Command (Canada COM; whose functions have been subsumed by Canadian Joint Operations Command or "CJOC") embarked on a complex operational planning effort of the kind described above. The CJOC Concept of Operations for Domestic CBRN Defence [1] resulted from that effort and describes, in high-level terms, how the Canadian Armed Forces (CAF) would assist civil authorities with respect to a chemical, biological, radiological, nuclear (CBRN), or hazardous material (HAZMAT) event in Canada. In turn, the concept will frame CJOC's development of a detailed contingency plan (CONPLAN) concerning the CAF's responses to a range of potential domestic incidents involving CBRN or hazardous material releases.

The Canada COM/CJOC Operational Research and Analysis (OR&A) Team provided analytical support throughout the concept's development, which was led by the Force Development (FD) cells within Canada COM and CJOC. Specifically, OR&A provided the FD cells with analytical means to identify (as systematically as possible, given the timelines involved) key capability gaps that the concept should address. We also developed means for objectively comparing options for addressing such gaps. We did not address policy issues concerning the mandates of various government departments, since such considerations were beyond the scope of the analysis.

1.3 Aim and outline of report

This report describes the Vignette, Task, Requirement, and Option (VITRO) analyses approach, which we developed and applied to support CBRN-related concept development at Canada COM/CJOC. Though illustrated in the context of domestic CBRN event response, our approach can be adapted readily for application to a variety of other planning areas. To enable its broad distribution, this report presents the VITRO method in an unclassified manner, **using notional data throughout**. The classified VITRO inputs and associated results, which underpinned Canada COM/CJOC's concept development, are described in a previous report [2].

In the context of domestic CBRN event response, we developed the VITRO approach to address the four following questions:

1. For what types of domestic CBRN events should the CAF plan?

2. For such events, what tasks would the CAF likely be asked to perform?

3. To perform such tasks adequately, what would the CAF need?

4. Which force packages would respond well, given many possible CBRN events?

The VITRO approach addresses these questions in turn, via four distinct analyses. They are summarized as follows:

1. *Vignette analysis*: the identification of potential domestic CBRN events (vignettes) and the estimation of their relative probabilities of occurrence.

2. *Task analysis*: the identification of tasks associated with a potential domestic CBRN event response and the estimation of the probabilities that the CAF would be requested to perform them.

3. *Requirement analysis*: the estimation of quantities and training levels of personnel required for adequate task performance, when requested, within each vignette. We formulated hypothetical force packages for an option analysis, based on common thresholds within the requirements estimates.

4. *Option analysis*: the comparison of hypothetical force packages, based on the gap probabilities associated with each potential task.

This report's structure reflects these four analyses. In the following sections, an overview of the method employed during each analysis is provided, as well as a discussion of notional results and limitations. Additional details on specific aspects of the analyses are presented in annexes.

Throughout the report, the terms "CBRN event" and "CBRN defence" are meant to encompass releases of toxic industrial (i.e., hazardous) materials as well as CBRN warfare agents. Such usages are consistent with agreed North Atlantic Treaty Organization terminology [3].

2 Vignette analysis

Vignette analysis represents the initial component of the VITRO approach to concept development. It involves the construction of a sufficiently comprehensive set of vignettes whose probabilities of occurrence relative to the entire set are estimated subsequently.

2.1 Vignette sets

The quality of results obtained during vignette analysis depends strongly on the composition of the vignette set analysed. To enable valid results, there are a number of conditions that the vignette set should satisfy.

- The vignettes within a set should be well thought out and appropriately detailed.

- The quantity of vignettes considered should be large enough to span the relevant range of possibilities well, but limited enough to make their evaluation feasible.

- A set's vignettes should be agent-independent. That is, each vignette should describe a certain type of potential event but not involve more than one agent class or agent.

- The relative probabilities of a set's vignettes should be time-independent. For non-deliberate event types (e.g., natural phenomena or unintentional industrial accidents), this may be largely so. However, malicious acts are not generally time-independent, since an adversary can learn from a first attack and adapt his/her target selection and/or methods for a future one. Thus, the relative likelihoods of vignettes within a set prior to a deliberate attack could be different afterwards. Consequently, a vignette set should represent a range of "first use" situations, but would not apply to potential sequences of malicious acts.

- A set's vignettes should be sufficiently unlikely, such that a maximum of one such event may occur within a time frame of interest. Though our method can yield estimates regarding the nature of the "next" such event, it does not address subsequent potential events. Therefore, our method should not be used to estimate that number of events that may occur within a given period of time.

Two vignette sets are described below. The set used for Canada COM/CJOC concept development is discussed, to the extent possible in unclassified terms. A notional set created to illustrate the analytical method is also presented.

2.1.1 Canada COM/CJOC set

To provide context for Canada COM/CJOC concept development, a set of 12 domestic vignettes was compiled in consultation with FD staff. Each vignette involves the hypothetical dissemination of a weaponized chemical, biological, or radiological agent; a nuclear detonation; or a hazardous (i.e., toxic industrial) material release. We sought to construct a set that would be sufficiently representative of the broad range of potential domestic CBRN events, yet whose quantity of vignettes would not be too time-consuming to evaluate under workshop conditions. When selecting vignettes, we sought to include "worst plausible" cases over "worst possible" ones.

For the Canada COM/CJOC analysis, we selected ten vignettes from the United States' Department of Homeland Security's (US DHS) set of National Planning Scenarios [4]. We adjusted some vignettes' quantitative consequences, in an effort to tailor them for a Canadian context. To enhance the set's representativeness, we incorporated two additional vignettes. The first addition concerns the release of radioactive gas from a nuclear power generation station [5]. The second additional vignette was created by Canada Command's FD cell and describes an accidental, large-scale release of a toxic industrial chemical [6].

2.1.2 Notional set

To demonstrate our vignette analysis method here, we have created a notional set of 12 CBRN-related vignettes. In terms of agent class, the set consists of two chemical, four biological, two radiological, one nuclear, and three hazardous material vignettes.

We have not developed a narrative description for each notional vignette, since they are not required for the current purpose of illustration. For the Canada COM/CJOC analysis, we summarized such narratives as described in Annex A, to facilitate vignette likelihood estimation (as well as the task and requirement analyses described later).

To illustrate the discussion of our analytical approach, we have depicted the notional set's vignettes schematically in two equivalent forms. The first depiction (a Venn-diagram; Figure 1), presents the set's vignettes grouped by agent class. The figure's double-headed arrows signify pairwise comparisons that were made between and within agent classes. Such comparisons are discussed in Section 2.2.2. The second illustration (Figure 2) is a hierarchical representation, in which potential domestic CBRN events (topmost level) are decomposed first by agent class (middle tier), then by vignettes specific to each agent class (lowest level). For conciseness, we have denoted the agent classes using the symbols C (chemical), B (biological), R (radiological), N (nuclear), and H (hazardous material). The hierarchical diagram is a more natural one for understanding the data aggregation steps and conditional probability calculations described in Section 2.3. Both representations employ the notional vignette identifiers assigned in Table A-1. For example, we have associated the chemical vignettes C1 and C2 with the chemical agent class, in both figures.

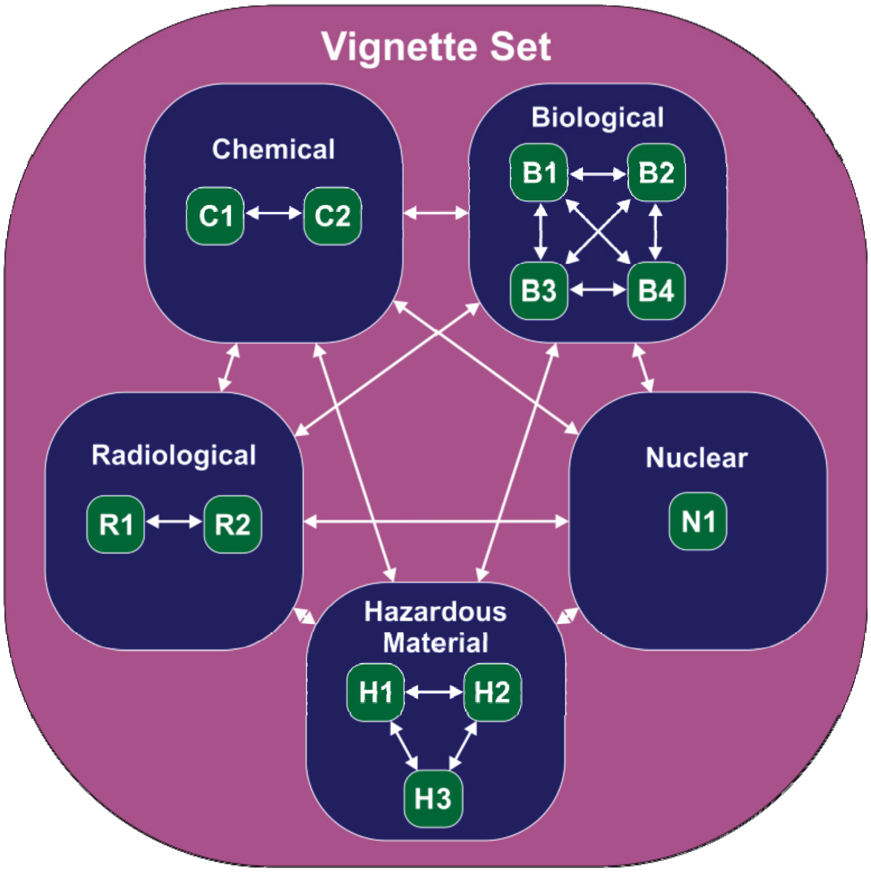

Figure 1: Venn-diagram representation of the notional vignette set depicting agent classes and pairwise comparisons made during the analysis.

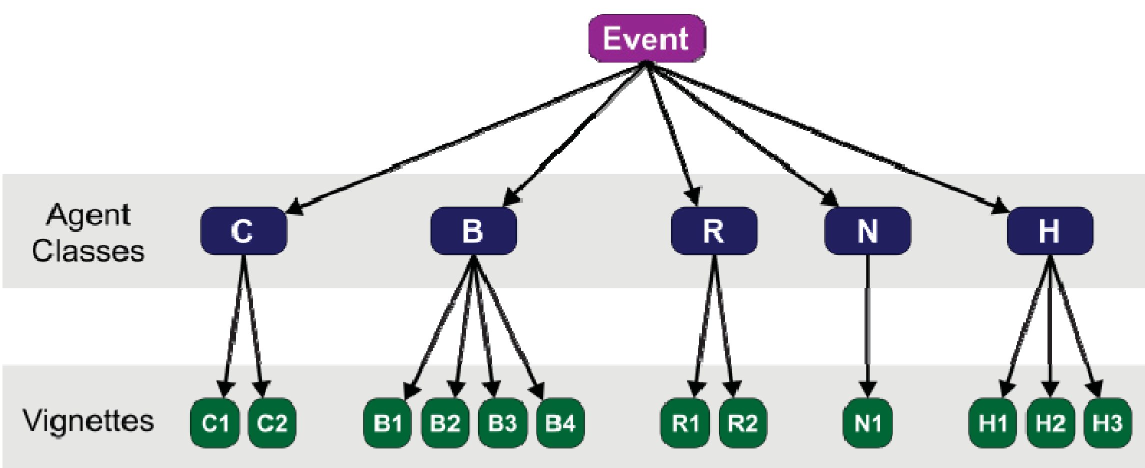

Figure 2: Hierarchical representation of notional domestic CBRN vignettes.

2.2 Pairwise estimation of relative vignette probabilities

Within a given set, vignettes' real-world probabilities of occurrence generally differ. For potential domestic CBRN events, such likelihood differences may span orders of magnitude. Thus, for many applications, one must calibrate a set prior to its use, by estimating its vignettes' probabilities in some fashion.

Vignette likelihoods may be estimated in either absolute or relative terms.

1. In an absolute approach, one estimates each vignette's probability of occurrence within a specific time frame, e.g., "that vignette has an *x*% chance of occurring during the next 10 years". Assuming that such a probability can be estimated, a large amount of reliable technical, intelligence, and/or other information is typically required to obtain accurate estimates.

2. In a relative approach, one requires a diverse vignette set that can reasonably approximate potential domestic CBRN events. Then, when assuming that such an event will occur, it will be similar to one of the set's vignettes. One needs only to determine which of those is the representative vignette. To do that, one must estimate the relative probability of occurrence (or "weight") of each vignette in the set, i.e., "if an event occurs, there is an *n*% chance of that vignette approximating it". To yield accurate estimates, this relative approach requires less information than the absolute one, since it does not entail projections concerning the frequency with which domestic CBRN events will occur (merely the nature of an event, when it occurs).

If a vignette set represents the broad range of potential events well, the two approaches described above are compatible. One can multiply a set's relative vignette probabilities by the estimated likelihood of an event occurring within a particular time frame, to approximate the set's absolute vignette probabilities during that period.

To support Canada COM/CJOC's concept development work, we adopted a relative approach, for two main reasons:

1. The concept development effort concerned CAF responses to domestic CBRN events if/when they occur. Before planning a response, one must assume that an event will occur and estimate the range and likelihoods of the event's possible natures. A relative approach is fully consistent with that assumption and well suited for making such estimates.

2. A relative approach required less information, yet sufficed for our purpose. The alternative (an absolute approach) involved estimating each vignette's likelihood of occurrence within a set time frame. Given that our knowledge of the current threat environment is imperfect – and that of a future one even more so – the results produced by an absolute approach would have been more uncertain. Moreover, such estimates can be highly subjective and contentious. So, including them in our analysis would have risked making our results unnecessarily controversial.

The estimation of vignettes' relative probabilities can be a challenging undertaking. Such CBRN events are rare or unprecedented, so historical data may have limited utility for estimating event likelihood. Furthermore, such estimates are typically generated during workshops, whose participants make subjective judgements based on imperfect knowledge of the current and future threat environments. Such judgements can be biased, depending on how estimates are elicited from participants and how they reason. Moreover, the accuracy of such estimates cannot be validated, since they pertain to potential events. Finally, planning efforts are inevitably predicated on certain assumptions – and Canada COM/CJOC's concept development for domestic CBRN event response was no exception. While conducting our analysis, we sought to strike an appropriate balance between the "accuracy" of estimates and the required time and resource investments needed to obtain them. Thereafter, we strove to aggregate the estimates in a mathematically valid manner, to yield results with direct utility for senior-level decision making.

In the following sections, we discuss the manner in which estimates were obtained (Section 2.2.1), the types of estimates that served as inputs to our analysis (Section 2.2.2), the calculations performed on them to yield relative probabilities (Section 2.3), and the means used to visualize the results (Section 2.4). For illustrative purposes, notional data are used throughout the text.

2.2.1 Elicitation of estimates

The acquisition of reliable estimates regarding an uncertain future is a challenging endeavour, to which much consideration has been devoted [7]. An obvious prerequisite is the availability of persons with suitably deep and pertinent knowledge. However, such persons' biases and ways of reasoning are also important [8]. Moreover, the manner in which information is elicited from them can also affect the estimates obtained [9].

The elicitation approach adopted during Canada COM/CJOC's concept development work aimed to strike a favourable balance between such considerations, given prevailing time and resource constraints. We facilitated a workshop in which estimates were elicited from Canada COM J2 (intelligence) representatives and a CBRN advisor, on a consensus basis. Such facilitation involved focusing the discussion, challenging participants' assumptions and reasoning, seeking consensus, ensuring that estimates were stated unambiguously, and applying the elicitation method rigorously. At the workshop's outset, we provided workshop participants with historical data on CBRN events that have occurred worldwide, to inform their deliberations.

We developed a spreadsheet-based tool for use during the workshop, which enabled data capture and real-time self-consistency assessment of participants' estimates.

2.2.2 Pairwise comparison method

To obtain estimates of the vignettes' relative probabilities (or weights), we used a weight assignment method similar to that used in the Analytic Hierarchy Process (AHP) [10]-[11], which decomposes decision problems into a hierarchy of sub-problems (as in Figure 2). Our method enabled workshop participants to weigh vignettes by comparing only two of them at a time – a process that is arguably easier and more accurate than trying to compare the set's 12 vignettes simultaneously.[1] We believed that considering fewer vignettes at once would also help to focus group discussions, lead participants to consider each vignette more thoroughly, and make it easier to achieve consensus regarding the estimates.

As an initial step, we grouped the Canada COM/CJOC set's vignettes in a manner analogous to that depicted for the notional set in Figure 1. In the diagram, each double-headed arrow represents a pairwise estimate of relative probabilities made by workshop participants. For the notional set (as Figure 1 suggests), five rounds of pairwise comparisons are required, between:

1. all possible pairs of agent classes;

2. the pair of chemical vignettes;

3. all possible pairs of biological vignettes;

4. the pair of radiological vignettes; and

5. all possible pairs of hazardous material vignettes.

Pairwise comparisons are neither possible nor required for the nuclear agent class, since it contains a single vignette. That is, vignette N1 is assumed to be representative of any potential domestic nuclear event.

We first consider the round of comparisons between all possible pairs of agent classes. As Figure 1 illustrates, ten such comparisons can be made. These comparisons are listed individually as rows in Table 1, along with notional values for each. The table's "agent classes compared" column lists the agent classes considered during each comparison. On a consensus basis, workshop participants selected the agent class that they believed is more likely to be associated with a domestic CBRN event (see the notional table's "more likely class" column). They then estimated the factor by which that would be so (i.e., "how many times more likely"), relative to the less likely agent class. Analogous notional estimates are listed in the table's "relative likelihood" column.

To frame our discussion of relative agent class likelihoods more explicitly, we introduce the following notation. If a domestic CBRN event occurs, let the relative probability of it involving an agent of class a be represented by a conditional probability of the form p_a. Then, given a domestic CBRN event, the relative likelihood of a chemical warfare agent release is p_C, the

[1] The first formal use of pairwise comparisons for measurement purposes was by Thurstone [12].

relative probability of a biological warfare agent dissemination is p_B, etc. Since these quantities represent a complete set of relative probabilities for agent class, they sum to unity, i.e.,

$$p_C + p_B + p_R + p_N + p_H = 1 . \qquad (1)$$

Using this notation, the result of each notional pairwise comparison in Table 1 can be expressed as two implied ratios. These implied relationships are also tabulated in Table 1. For instance, the first pairwise comparison concerns the chemical and biological agent classes and indicates that a biological release is 40 times more likely than a chemical one. As a fraction, this relationship can be expressed as either $p_B / p_C = 40$ or as its reciprocal, i.e., $p_C / p_B = 1/40$.

Table 1: Notional data for pairwise comparisons of agent class likelihoods.

Agent Classes Compared	More Likely Agent Class	Relative Likelihood	Implied Relationships
C & B	B	40	$\frac{p_B}{p_C} = 40$; $\frac{p_C}{p_B} = \frac{1}{40}$
C & R	R	60	$\frac{p_R}{p_C} = 60$; $\frac{p_C}{p_R} = \frac{1}{60}$
C & N	N	20	$\frac{p_N}{p_C} = 20$; $\frac{p_C}{p_N} = \frac{1}{20}$
C & H	H	40	$\frac{p_H}{p_C} = 40$; $\frac{p_C}{p_H} = \frac{1}{40}$
B & R	R	2	$\frac{p_R}{p_B} = 2$; $\frac{p_B}{p_R} = \frac{1}{2}$
B & N	B	1	$\frac{p_B}{p_N} = \frac{p_N}{p_B} = 1$
B & H	H	2	$\frac{p_H}{p_B} = 2$; $\frac{p_B}{p_H} = \frac{1}{2}$
R & N	R	1	$\frac{p_R}{p_N} = \frac{p_N}{p_R} = 1$
R & H	R	3	$\frac{p_R}{p_H} = 3$; $\frac{p_H}{p_R} = \frac{1}{3}$
N & H	H	2	$\frac{p_H}{p_N} = 2$; $\frac{p_N}{p_H} = \frac{1}{2}$

During the Canada COM/CJOC analysis, analogous pairwise comparison rounds were conducted for vignettes specific to each agent class. We illustrate these subsequent rounds in terms of the notional vignette set, as follows. As Figure 1 indicates, the additional numbers of pairwise comparisons required were one for the chemical vignettes C1 and C2; six for the biological vignettes B1 to B4; one for the radiological vignettes R1 and R2, none for the lone nuclear vignette N1, and three for the hazardous material vignettes H1 to H3. Notional results for these four additional rounds of pairwise comparisons are presented in Table 2.

Table 2: Notional data for pairwise comparisons of vignette likelihoods within each agent class.

Vignettes Compared	More Likely Vignette	Relative Likelihood	Implied Relationships
C1 & C2	C1	2	$\frac{p_{C1}}{p_{C2}} = 2$; $\frac{p_{C2}}{p_{C1}} = \frac{1}{2}$
B1 & B2	B2	2	$\frac{p_{B2}}{p_{B1}} = 2$; $\frac{p_{B1}}{p_{B2}} = \frac{1}{2}$
B1 & B3	B3	10	$\frac{p_{B3}}{p_{B1}} = 10$; $\frac{p_{B1}}{p_{B3}} = \frac{1}{10}$
B1 & B4	B1	30	$\frac{p_{B1}}{p_{B4}} = 30$; $\frac{p_{B4}}{p_{B1}} = \frac{1}{30}$
B2 & B3	B3	4	$\frac{p_{B3}}{p_{B2}} = 4$; $\frac{p_{B2}}{p_{B3}} = \frac{1}{4}$
B2 & B4	B2	100	$\frac{p_{B2}}{p_{B4}} = 100$; $\frac{p_{B4}}{p_{B2}} = \frac{1}{100}$
B3 & B4	B3	200	$\frac{p_{B3}}{p_{B4}} = 200$; $\frac{p_{B4}}{p_{B3}} = \frac{1}{200}$
R1 & R2	R2	2	$\frac{p_{R2}}{p_{R1}} = 2$; $\frac{p_{R1}}{p_{R2}} = \frac{1}{2}$
H1 & H2	H2	400	$\frac{p_{H2}}{p_{H1}} = 400$; $\frac{p_{H1}}{p_{H2}} = \frac{1}{400}$
H1 & H3	H3	50	$\frac{p_{H3}}{p_{H1}} = 50$; $\frac{p_{H1}}{p_{H3}} = \frac{1}{50}$
H2 & H3	H2	10	$\frac{p_{H2}}{p_{H3}} = 10$; $\frac{p_{H3}}{p_{H2}} = \frac{1}{10}$

To describe such estimates concisely, we introduce additional notation. That is, given a domestic event involving agent class *a*, we represent the relative likelihood of the i^{th} vignette pertaining to that agent class by a conditional probability of the form p_{ai}. For instance, p_{C1} denotes the relative probability of the first vignette within the subset of vignettes involving chemical warfare agents, C1. These relative probabilities satisfy the following agent class-specific normalization relationships:

$$p_{C1} + p_{C2} = 1, \quad (2)$$

$$p_{B1} + p_{B2} + p_{B3} + p_{B4} = 1, \quad (3)$$

$$p_{R1} + p_{R2} = 1, \quad (4)$$

$$p_{N1} = 1, \text{ and} \quad (5)$$

$$p_{H1} + p_{H2} + p_{H3} = 1. \quad (6)$$

Using this notation, the result of each pairwise comparison in Table 2 has been expressed as two reciprocal implied relationships, in the table's "Implied Relationships" column.

Since this method compares the relative likelihoods of pairs of vignettes in isolation, it is possible (if not probable) that a complete set of pairwise estimates may be internally inconsistent. For example, consider the collection of notional estimates for agent class likelihoods in Table 1. There, the sixth estimate indicates that events involving either biological or nuclear agents are equally likely, i.e., $p_B = p_N$. Similarly, the eighth estimate suggests that radiological events and nuclear events have equal likelihoods, i.e., $p_R = p_N$. Together, these estimates imply that domestic events involving biological, radiological, or nuclear agents are equally probable, i.e., $p_B = p_R = p_N$. However, this implication contradicts the fifth estimate, which states that radiological events are twice as likely as biological ones, i.e., $p_R = 2p_B$. Thus, the set of notional estimates for agent class likelihoods is internally inconsistent.[2]

Such internal inconsistency is a potential drawback of pairwise comparison approaches – but it is an avoidable one. During the Canada COM vignette analysis workshop, we quantitatively assessed the degree of inconsistency of each set of pairwise estimates, in real time (our method is described in Section 2.3). We tolerated some inconsistency, since the estimates were uncertain and the workshop was time-constrained. However, when a set's degree of inconsistency exceeded a threshold value, we brought a subset of inconsistent estimates to the participants' attention.[3] Following additional discussion, participants revised one or more of their estimates, to improve the set's consistency.

[2] Such inconsistency is discussed more formally in Section 2.3.1.

[3] Section 2.3.1 describes our consistency metric for the estimates and the threshold value that we used.

2.3 Aggregation of pairwise probability estimates

The ultimate outputs of our vignette analysis each consist of the estimated probability of a vignette relative to its entire set, given a domestic CBRN event. Such results can be used as weighting factors in other assessments, to account for differences in vignette likelihoods (as we do in the task and option analyses described in Sections 3 and 5). However, the probability estimates discussed in Section 2.2.2 each express the relative likelihood of a vignette versus another one – not with respect to all vignettes in a set. Thus, to obtain the desired relative probability of each vignette with respect to its entire set, such pairwise estimates must be aggregated. To that end, we used an approach during the Canada COM vignette analysis that:

1. aggregates the pairwise data in a transparent and mathematically valid manner,

2. provides a measure of the pairwise estimates' degree of internal consistency, and

3. enables reconsideration and revision of inconsistent estimates in real time during a workshop.

We aggregated pairwise comparison data in a series of steps, which we describe below with reference to the hierarchical arrangement of notional vignettes in Figure 2. Given a domestic CBRN event (denoted by the top tier in the figure), the agent class involved will be one of the five possibilities present in the figure's middle level. However, the five agent classes' potential involvements are not equally likely. Thus, the first step involves aggregating the pairwise comparison data for agent class (Table 1), to yield the relative probability of each agent class being involved in the event. The remaining aggregation steps involve the middle and bottom tiers in the figure, as follows. Given a domestic CBRN event involving a specific agent class, one (in the nuclear case) or more (in the other four cases) vignettes could approximate it. Where multiple vignettes pertain to an agent class, an additional aggregation step is required. For instance, given a biological event, the pairwise comparison data for vignettes B1 to B4 (Table 2) must be aggregated to yield each vignette's relative probability of approximating the biological event.

Once all aggregation steps are complete, the desired relative likelihood for each vignette relative to the set (whose symbolic representation is of the form P_{ai}) can be obtained by taking the product of the appropriate conditional probabilities. For example, given a domestic CBRN event, the relative likelihood that vignette B3 will approximate it (i.e., P_{B3}) is equal to the product of (a) the probability that a domestic event involves a biological agent p_B and (b) the probability that vignette B3 is representative of a biological event p_{B3}.

We performed each aggregation step using an eigenvector method. Our aggregation of the notional pairwise comparison data for agent class (Table 1) is presented in Section 2.3.1. Thereafter, we describe the aggregation of pairwise comparison data for vignettes within specific agent classes (Table 2) in Section 2.3.2. We discuss the final calculation of each vignette's probability relative to the notional set in Section 2.3.3.

2.3.1 Data aggregation for agent classes

We illustrate our eigenvector-based aggregation approach using the notional pairwise estimates of agent class likelihood (Table 1). Each such estimate describes the relative likelihood of a potential domestic CBRN event involving a particular agent class versus another, specific one, e.g., p_B / p_C. But, what do the pairwise estimates collectively imply about the probability of a potential domestic CBRN event involving a specific agent class? For instance, how might we aggregate such estimates to ascertain the estimated fraction of such events involving biological agents, i.e., p_B?

We address such questions by first arranging the quantities whose values we seek (i.e., the relative likelihoods of each agent class being involved in a domestic CBRN event) in vector form V_A, such that

$$V_A = \begin{bmatrix} p_C \\ p_B \\ p_R \\ p_N \\ p_H \end{bmatrix}. \tag{7}$$

Next, in analogy with the AHP approach [10]-[11], we construct a comparison matrix for the agent classes M_A (Equation (8)), which we populate based on the implied relationships listed in Table 1. In the matrix, each agent class is associated with both a row and a column. Each matrix element corresponds to how many times more likely its row's agent class is to be used in a domestic CBRN event than its column's agent class.[4]

$$M_A \equiv \begin{bmatrix} \frac{p_C}{p_C} & \frac{p_C}{p_B} & \frac{p_C}{p_R} & \frac{p_C}{p_N} & \frac{p_C}{p_H} \\ \frac{p_B}{p_C} & \frac{p_B}{p_B} & \frac{p_B}{p_R} & \frac{p_B}{p_N} & \frac{p_B}{p_H} \\ \frac{p_R}{p_C} & \frac{p_R}{p_B} & \frac{p_R}{p_R} & \frac{p_R}{p_N} & \frac{p_R}{p_H} \\ \frac{p_N}{p_C} & \frac{p_N}{p_B} & \frac{p_N}{p_R} & \frac{p_N}{p_N} & \frac{p_N}{p_H} \\ \frac{p_H}{p_C} & \frac{p_H}{p_B} & \frac{p_H}{p_R} & \frac{p_H}{p_N} & \frac{p_H}{p_H} \end{bmatrix} = \begin{bmatrix} 1 & 1/40 & 1/60 & 1/20 & 1/40 \\ 40 & 1 & 1/2 & 1 & 1/2 \\ 60 & 2 & 1 & 1 & 3 \\ 20 & 1 & 1 & 1 & 1/2 \\ 40 & 2 & 1/3 & 2 & 1 \end{bmatrix} \tag{8}$$

[4] By construction, such pairwise comparison matrices are positive reciprocal.

Note that the comparison matrix M_A lacks the transitive property, i.e., $\frac{p_i}{p_k} = \frac{p_i}{p_j} \cdot \frac{p_j}{p_k}$ does not hold for all agent class indices *i*, *j*, and *k*. This reflects (in a more formal mathematical sense) the lack of internal consistency of Table 1's agent class estimates, which we illustrated by example in Section 2.2.2.

In analogy with the AHP approach [10]-[11], we solve the following eigenvalue equation for matrix M_A to obtain the relative probabilities of each agent class being involved in a domestic event,[5] which are contained in the vector V_A:

$$M_A \, V_A = \lambda_{A\max} \, V_A . \tag{9}$$

Here, λ_{Amax} represents the principal eigenvalue and V_A is the corresponding principal eigenvector. The range of the principal eigenvalue is $\lambda_{A\max} \geq n_A$, where $n_A = 5$ is the number of agent classes (i.e., the order of the 5×5 comparison matrix M_A). Had the matrix M_A been internally consistent, the limiting case $\lambda_{A\max} = n_A$ would have resulted. Since M_A is inconsistent, λ_{Amax} will exceed n_A, so the difference $\lambda_{A\max} - n_A$ can be used to gauge the inconsistency of the agent class likelihood estimates in Table 1.

The most commonly used measure of matrix inconsistency was developed by Saaty [10], who defined the *consistency ratio CR* for a generic comparison matrix of order *n* having principal eigenvalue λ_{max} as follows:

$$CR = \frac{CI}{CV} = \left(\frac{\lambda_{\max} - n}{n-1} \right) \left(\frac{1}{CV} \right), \tag{10}$$

where *CI* is known as the *consistency index* and

CV denotes a *comparative value* that depends implicitly on the comparison matrix' order, as illustrated in Table 3 [13].

The comparative value *CV* for each order is calculated from many randomly generated comparison matrices of identical size. Each comparative value serves to normalize its associated consistency index *CI*, thus rendering the consistency ratio *CR* expression (Equation (10)) independent of comparison matrix order. Such order-independence enables the consistency ratios of differently sized matrices to be compared directly. Fully consistent matrices are characterized by consistency ratios of $CR = 0$ whereas $CR > 0$ for inconsistent matrices. Since it is highly probable that any set of pairwise estimates obtained from workshop participants will be inconsistent, subjective judgement concerning what constitutes an acceptable degree of inconsistency is required. AHP practitioners routinely use the threshold value set by Saaty [10].

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[5] When a comparison matrix is inconsistent (as is the agent class matrix M_A used here), the relative probabilities which comprise the elements of the principal eigenvector are approximate.

That is, they consider comparison matrices to be acceptably inconsistent if their consistency values are in the range $0 < CR < 0.1$. During the Canada COM vignette analysis, we adopted the same criterion to judge whether empirical comparison matrices were acceptably inconsistent or not.

Table 3: Comparative values as a function of matrix order for a generic matrix.

Order of Comparison Matrix ***n***	**Comparative Value** ***CV***
2	2.00
3	0.52
4	0.89
5	1.11
6	1.25
7	1.35
8	1.40
9	1.45
10	1.49

Having described our approach for assessing comparison matrix inconsistency, we now complete the notional relative probability calculation of each agent class being involved in a domestic CBRN event (Equation (7)). To that end, we solved Equation (9) using the iterative "power method" [14] to obtain the principal eigenvalue $\lambda_{A\max} = 5.32$. The agent class comparison matrix M_A (Equation (8)) is of order $n_A = 5$ and so has a corresponding comparative value of $CV_A = 1.11$ (Table 3). Together, these yield a consistency ratio of $CR_A = 0.072$ (Equation (10)). This value is in the conventional range $0 < CR_A < 0.1$, which implies that the agent class comparison matrix M_A is inconsistent, but to an acceptable extent. Consequently, we obtain approximations of the desired relative probability for each agent class directly from the other result of the power method solution of Equation (9) – the normalized principal eigenvector V_A:

$$V_A = \begin{bmatrix} p_C \\ p_B \\ p_R \\ p_N \\ p_H \end{bmatrix} = \begin{bmatrix} 0.006 \\ 0.172 \\ 0.383 \\ 0.186 \\ 0.252 \end{bmatrix}. \quad (11)$$

Such results contain the answer to the example question that we posed to motivate our discussion, at the outset of Section 2.3.1. That is, the notional estimated fraction of potential domestic CBRN events involving biological agents is approximately $p_B = 0.172$ or 17.2%. The results also contain answers to analogous questions concerning the other four agent classes considered here.

2.3.2 Data aggregation for vignettes within a particular agent class

We used analogous eigenvector approaches to estimate the probabilities of vignettes relative to their respective agent classes (i.e., for each subset of vignettes in the lowest tier of Figure 2). Since each of the requisite aggregation steps is analogous to that described for agent classes in Section 2.3.1, we provide only a brief, concurrent description for all remaining steps below. First, we constructed vectors using the probabilities of non-nuclear vignettes[6] relative to their particular agent classes p_{ai}, i.e.,

$$V_C = \begin{bmatrix} p_{C1} \\ p_{C2} \end{bmatrix}, \tag{12}$$

$$V_B = \begin{bmatrix} p_{B1} \\ p_{B2} \\ p_{B3} \\ p_{B4} \end{bmatrix}, \tag{13}$$

$$V_R = \begin{bmatrix} p_{R1} \\ p_{R2} \end{bmatrix}, \text{ and} \tag{14}$$

$$V_H = \begin{bmatrix} p_{H1} \\ p_{H2} \\ p_{H3} \end{bmatrix}, \tag{15}$$

Here, the vectors V_C, V_B, V_R, and V_H pertain to the chemical, biological, radiological, and hazardous material agent classes, respectively.

Next, for vignettes corresponding to each non-nuclear agent class, we formed an analogous comparison matrix that we populated based on the implied relationships listed in Table 2, i.e.,

$$M_C \equiv \begin{bmatrix} \frac{p_{C1}}{p_{C1}} & \frac{p_{C1}}{p_{C2}} \\ \frac{p_{C2}}{p_{C1}} & \frac{p_{C2}}{p_{C2}} \end{bmatrix} = \begin{bmatrix} 1 & 2 \\ 1/2 & 1 \end{bmatrix}, \tag{16}$$

[6] Since only one vignette is associated with the nuclear agent class, aggregation is unnecessary. The sought-after result (i.e., $p_{N1} = 1$) is given by the trivial normalization condition (i.e., Equation (5)).

$$M_B \equiv \begin{bmatrix} \frac{p_{B1}}{p_{B1}} & \frac{p_{B1}}{p_{B2}} & \frac{p_{B1}}{p_{B3}} & \frac{p_{B1}}{p_{B4}} \\ \frac{p_{B2}}{p_{B1}} & \frac{p_{B2}}{p_{B2}} & \frac{p_{B2}}{p_{B3}} & \frac{p_{B2}}{p_{B4}} \\ \frac{p_{B3}}{p_{B1}} & \frac{p_{B3}}{p_{B2}} & \frac{p_{B3}}{p_{B3}} & \frac{p_{B3}}{p_{B4}} \\ \frac{p_{B4}}{p_{B1}} & \frac{p_{B4}}{p_{B2}} & \frac{p_{B4}}{p_{B3}} & \frac{p_{B4}}{p_{B4}} \end{bmatrix} = \begin{bmatrix} 1 & 1/2 & 1/10 & 30 \\ 2 & 1 & 1/4 & 100 \\ 10 & 4 & 1 & 200 \\ 1/30 & 1/100 & 1/200 & 1 \end{bmatrix}, \tag{17}$$

$$M_R \equiv \begin{bmatrix} \frac{p_{R1}}{p_{R1}} & \frac{p_{R1}}{p_{R2}} \\ \frac{p_{R2}}{p_{R1}} & \frac{p_{R2}}{p_{R2}} \end{bmatrix} = \begin{bmatrix} 1 & 1/2 \\ 2 & 1 \end{bmatrix}, \text{ and} \tag{18}$$

$$M_H \equiv \begin{bmatrix} \frac{p_{H1}}{p_{H1}} & \frac{p_{H1}}{p_{H2}} & \frac{p_{H1}}{p_{H3}} \\ \frac{p_{H2}}{p_{H1}} & \frac{p_{H2}}{p_{H2}} & \frac{p_{H2}}{p_{H3}} \\ \frac{p_{H3}}{p_{H1}} & \frac{p_{H3}}{p_{H2}} & \frac{p_{H3}}{p_{H3}} \end{bmatrix} = \begin{bmatrix} 1 & 1/400 & 1/50 \\ 400 & 1 & 10 \\ 50 & 1/10 & 1 \end{bmatrix}, \tag{19}$$

where the comparison matrices M_C, M_B, M_R, and M_H pertain to the chemical, biological, radiological, and hazardous material agent classes, respectively.

We then constructed an analogous eigenvalue equation for vignettes pertaining to each non-nuclear agent class, namely,

$$M_C \, V_C = \lambda_{C\max} \, V_C, \tag{20}$$

$$M_B \, V_B = \lambda_{B\max} \, V_B, \tag{21}$$

$$M_R \, V_R = \lambda_{R\max} \, V_R, \text{ and} \tag{22}$$

$$M_H \, V_H = \lambda_{H\max} \, V_H, \tag{23}$$

where λ_{Cmax}, λ_{Bmax}, λ_{Rmax}, and λ_{Hmax} represent the principal eigenvalues corresponding to the chemical, biological, radiological, and hazardous material agent classes, respectively. Solving these equations approximately via the power method yields the agent class-specific principal eigenvalues and consistency ratios listed in Table 4.

Table 4: Principal eigenvalues and consistency ratios by agent class for the notional vignette set.

Agent Class	Principal Eigenvalue	Consistency Ratio
Chemical	$\lambda_{C\max} = 2.00$	$CR_{C\max} = 0.000$
Biological	$\lambda_{B\max} = 4.06$	$CR_{B\max} = 0.023$
Radiological	$\lambda_{R\max} = 2.00$	$CR_{R\max} = 0.000$
Hazardous Material	$\lambda_{H\max} = 3.01$	$CR_{H\max} = 0.005$

Consistency ratios of zero were obtained for the chemical ($CR_{C\max} = 0.000$) and radiological ($CR_{R\max} = 0.000$) agent classes, which indicate that internally consistent sets of estimates were obtained in both cases.[7] The consistency ratios for the vignettes associated with the biological ($CR_{B\max} = 0.023$) and hazardous material ($CR_{H\max} = 0.005$) agent classes each exceed zero but are less than 0.1. Thus, their associated sets of pairwise comparisons are inconsistent, but to an acceptable degree.

We obtained the non-nuclear vignettes' probabilities relative to their respective agent classes by solving their associated eigenvalue equations (Equations (20)-(23)) for their principal eigenvectors, which are:

$$V_C = \begin{bmatrix} p_{C1} \\ p_{C2} \end{bmatrix} = \begin{bmatrix} 0.667 \\ 0.333 \end{bmatrix}, \tag{24}$$

$$V_B = \begin{bmatrix} p_{B1} \\ p_{B2} \\ p_{B3} \\ p_{B4} \end{bmatrix} = \begin{bmatrix} 0.083 \\ 0.202 \\ 0.713 \\ 0.003 \end{bmatrix}, \tag{25}$$

$$V_R = \begin{bmatrix} p_{R1} \\ p_{R2} \end{bmatrix} = \begin{bmatrix} 0.333 \\ 0.667 \end{bmatrix}, \text{ and} \tag{26}$$

[7] Since only two vignettes pertained to each such agent class, only a single pairwise comparison was necessary in each case. Since two or more pairwise comparisons are needed for potential inconsistency to arise, the observed internal consistency of both sets was inevitable.

$$V_H = \begin{bmatrix} p_{H1} \\ p_{H2} \\ p_{H3} \end{bmatrix} = \begin{bmatrix} 0.002 \\ 0.901 \\ 0.097 \end{bmatrix}. \tag{27}$$

2.3.3 Calculation of vignette probabilities relative to an entire set, P_{ai}

As a prelude to calculating the probability of each vignette with respect to the notional set, we have consolidated various intermediate results in Table 5. All tabulated values pertain to the notional vignette set. The table incorporates the relative probabilities of each agent class being involved in a domestic CBRN event (p_a; Equation (11)) as well as the relative probability of each vignette with respect to its agent class (p_{ai}; Equations (5) and (24)-(27)).

The final results of the vignette analysis are listed in Table 5's rightmost column, i.e., the overall relative probabilities of all vignettes with respect to the notional set. Each such probability is of the form P_{ai}, which corresponds to the likelihood of *i*th vignette of agent class *a* approximating a domestic CBRN event. As noted in Section 2.3, the overall vignette likelihoods P_{ai} are calculated by taking the product of appropriate conditional probabilities. More specifically, the overall likelihood for each vignette P_{ai} is calculated by taking the product of the associated agent class' probability p_a (Table 5, second column) and the vignette's relative probability within that agent class p_{ai} (Table 5, fourth column), i.e.,

$$P_{ai} = p_a \times p_{ai}. \tag{28}$$

For example, the estimated relative likelihood of a domestic radiological event is $p_R = 0.383$. Further, vignette R1 is expected to approximate one-third of domestic radiological events ($p_{R1} = 0.333$). By multiplying these values, we obtain an estimated likelihood of vignette R1 approximating a potential domestic CBRN event of $P_{R1} = 0.1276$ or roughly 13%.

Table 5: Relative probabilities of each agent class, each vignette with respect to its agent class, and each vignette with respect to the notional set.

Agent Class	Agent Class Probability	Vignette	Vignette Probabilities	
			Within Agent Class	Within Notional Set
Chemical	$p_C = 0.006$	C1	$p_{C1} = 0.667$	$P_{C1} = 0.0041$
		C2	$p_{C2} = 0.333$	$P_{C2} = 0.0020$
Biological	$p_B = 0.172$	B1	$p_{B1} = 0.083$	$P_{B1} = 0.0143$
		B2	$p_{B2} = 0.202$	$P_{B2} = 0.0349$
		B3	$p_{B3} = 0.713$	$P_{B3} = 0.1233$
		B4	$p_{B4} = 0.003$	$P_{B4} = 0.0005$
Radiological	$p_R = 0.383$	R1	$p_{R1} = 0.333$	$P_{R1} = 0.1276$
		R2	$p_{R2} = 0.667$	$P_{R2} = 0.2552$
Nuclear	$p_N = 0.186$	N1	$p_{N1} = 1.000$	$P_{N1} = 0.1860$
Hazardous Material	$p_H = 0.252$	H1	$p_{H1} = 0.002$	$P_{H1} = 0.0005$
		H2	$p_{H2} = 0.901$	$P_{H2} = 0.2271$
		H3	$p_{H3} = 0.097$	$P_{H3} = 0.0245$

2.4 Visualization of aggregated vignette probabilities, P_{ai}

We represented the results of the Canada COM/CJOC vignette analysis using a logarithmic plot, since the relative vignette probabilities spanned multiple orders of magnitude. Since our spreadsheet-based tool calculated such probabilities in real time, we were able to present them graphically to participants, towards the end of the Canada COM workshop. This provided an additional check on the data, since it enabled participants to consider the aggregated vignette probabilities holistically. In the Canada COM/CJOC case, little additional discussion was required for workshop participants to agree that the plotted vignette probabilities were reasonably consistent with their collective expectations.

For illustration purposes, we have depicted the notional set's results in a manner similar to that used during the Canada COM workshop, in Figure 3. There, we have grouped vignettes by agent class and plotted their probabilities relative to the entire notional set on a logarithmic scale. Various inferences can be drawn using such plots. The following observations are predicated on the notional data and are offered only to illustrate how the plots should be interpreted:

- In agent class-specific terms, domestic radiological events are estimated to be the most likely (~38%). However, domestic hazardous material (~25%), nuclear (~19%), biological (~17%)

incidents have roughly comparable (though lesser) likelihoods. The estimated probability of domestic chemical events (~0.6%) is much lower than those of other agent classes.

- The notional probabilities for specific vignettes span roughly three orders of magnitude and form four clusters, i.e., those with likelihoods of (a) a few tens of percent, (b) a few percent, (c) a few tenths of a percent, and (d) several hundredths of a percent.

- Given a domestic CBRN event, the most likely vignettes and their approximate probabilities are: R2 (26%), H2 (23%), N1 (19%), R1 (13%), and B3 (12%). Collectively, these five vignettes represent ~92% of potential domestic CBRN events. Less probable vignettes with likelihoods at the few-percent level are B2 (~3%), H3 (~2%), and B1 (~1%). Vignettes C1 (~0.4%) and C2 (~0.2%) are even less probable whereas vignettes B4 (~0.05%) and H1 (~0.05%) are less likely still.

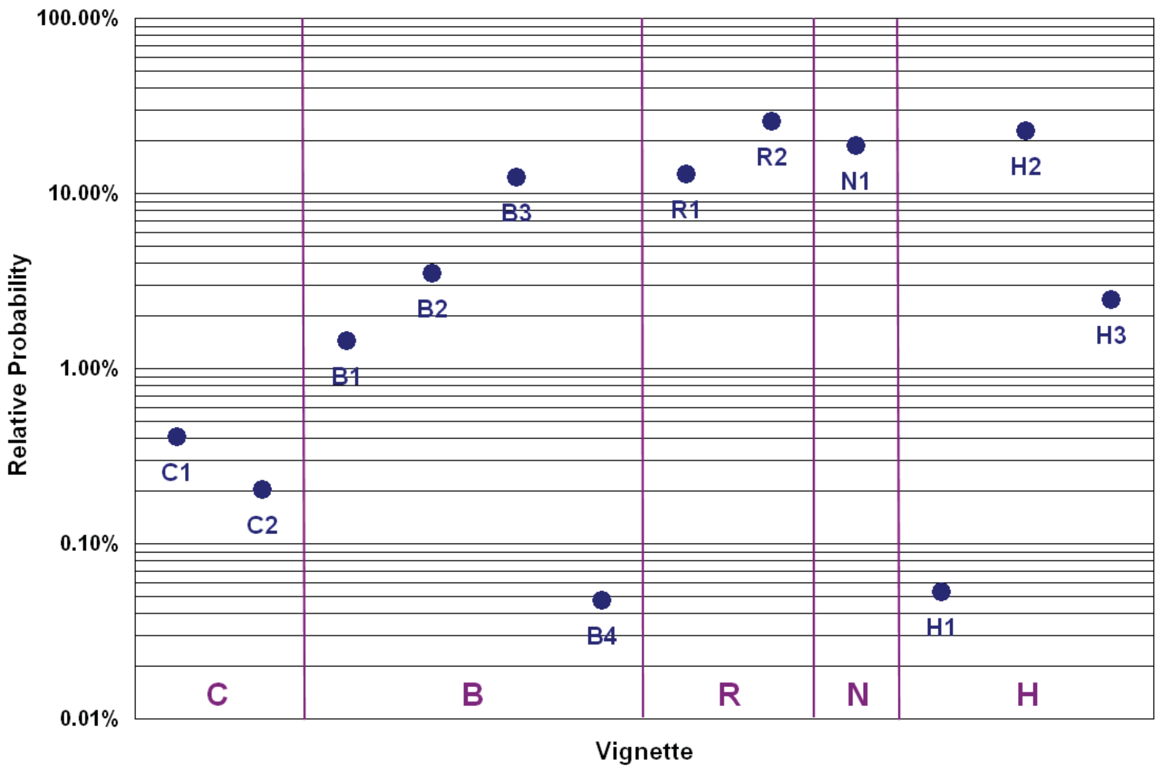

Figure 3: Relative probabilities of vignettes within the notional set, grouped by agent class, i.e., chemical (C), biological (B), radiological (R), nuclear (N), and hazardous material (H).

2.5 Discussion

Vignette analysis represents the initial component of the VITRO approach described in this report. Within that larger context, relative vignette probabilities depicted in Figure 3 represent intermediate results that constitute inputs to the task and option analyses presented in Sections 3 and 5. Alternatively, when conducting risk assessments, our vignette analysis method (or analogues of it) could be used to estimate vignettes' likelihoods, prior to gauging their consequences. During 2013, the Operational Analysis Working Group (OAWG) under the four-nation Chemical, Biological, and Radiological Memorandum of Understanding (CBR MOU) [15] agreed to adopt our method to assess vignette likelihoods as part of its larger risk assessment efforts.

Canada COM/CJOC concept developers and decision makers also embraced the vignette analysis method and its results. They valued (a) the reduced complexity, enhanced focus, and structured approach engendered by the use of pairwise comparisons for estimating vignette likelihoods; (b) the rigorous and transparent means of aggregating pairwise estimates; and (c) the relative simplicity and comprehensibility of the logarithmic plot used to depict the final results. An additional benefit was the ability to assess estimates' consistency in real time during a workshop, in order to revisit them with participants.

The method (as it was applied during Canada COM/CJOC concept development) has some limitations. For instance, since our method involves estimating the relative probabilities of vignettes, adding or removing vignettes from a set would modify certain results. Therefore, the results of analyses conducted on different vignette sets may not be directly comparable. Consequently, it is vital to develop a well-founded and representative vignette set at the outset of a study.

Another limitation is that, although pairwise estimates were elicited systematically from workshop participants, their deliberations during each comparison were relatively unstructured and lacked anonymity. If additional time had been available, more structure and/or anonymity could have been introduced to participants' deliberations, using the Delphi method [16] or similar means.

Furthermore, although the pairwise estimates' degree of internal consistency was monitored and controlled, their uncertainties were not estimated or propagated using our vignette analysis method. Consequently, the notional probabilities derived from such estimates (Table 5) are stated without associated uncertainties. Since the likelihoods of potential domestic CBRN events are highly uncertain, it would be desirable to quantify and report such uncertainties in any future application of the method. During the Canada COM/CJOC vignette analysis, we were unable to devise means for quantifying such uncertainties, due to time constraints. However, an approach analogous to that described by Zahir [17] may be suitable.

3 Task analysis

In the aftermath of a domestic CBRN event, the CAF may be requested to perform various tasks in support of civil authorities. To serve as a starting point for Canada COM/CJOC's concept development, it was therefore vital to establish what the CAF likely would be asked to do, following such an event. That was a nontrivial undertaking, since the spectrum of potential tasks is broad and the likelihood of a performance request for a given task depends strongly on an event's circumstances. To address that complex issue systematically and provide the required starting point for Canada COM/CJOC planners, we developed the task analysis method described in this chapter.

Task analysis represents the second component of the VITRO approach to concept development. During the analysis, the likelihoods of being requested to perform particular tasks in the context of specific vignettes are estimated. Given such relative probability estimates and a sufficiently representative vignette set, the likelihood of being requested to perform a particular task in relation to an event can be calculated.

3.1 Task sets

The Canada COM/CJOC task analysis used a set containing 54 potential tasks or task types (Annex B) that the CAF might be requested to perform, with respect to a domestic CBRN event. The set's tasks were selected from a Canadian variant [18] of a US DHS document [19] by a member of Canada COM's FD cell or added at the discretion of a CBRN advisor. The set was assumed to be sufficiently comprehensive for analytical purposes, yet suitably concise for use in a workshop setting.

We divided the Canada COM/CJOC task set based on the four temporal phases (Table B-1) set out in Public Safety Canada's Federal Policy for Emergency Management [20]. The "prevention" and "preparedness" phases respectively precede a domestic CBRN event, whereas the respective "response" and "recovery" phases jointly comprise its aftermath. Response-phase tasks predominate within the set, since Canada COM/CJOC's concept development focused on potential consequence management activities.

In the Canada COM/CJOC task set, post-event tasks were subdivided, based on the spatial "zones" in which they would be conducted (Table B-1). Three such zones were used, namely, a "hot" zone (in which contaminants are present), a "cold" zone (which is free of such contaminants), and a "warm" zone (which represents a transition area between the hot and cold zones, where decontamination and related activities would be performed). We believe that such zones' use was conceptually helpful, as it facilitated workshop participants' discussions of task probabilities and the like.

To illustrate the task analysis method in this report, we use an analogous set of notional tasks. Such tasks are undefined and denoted by the labels T1 through T54. As will be seen, the notional task set is partitioned by temporal phase and spatial zone, as described above.

3.2 Vignette sets

A sufficiently comprehensive vignette set is required to provide context for the task analysis. Canada COM/CJOC's task analysis employed the organization's vignette set that was described in Section 2.1.1. For this report's illustrative purposes, we use the notional vignette set presented in Section 2.1.2 as well as the relative vignette probabilities P_{ai} associated with it (Table 5).

3.3 Estimation of task performance request probabilities

As noted previously, the likelihood that the CAF would be requested to perform a particular task regarding a domestic CBRN event is situation-dependent. Such likelihood estimates were elicited from participants during a series of workshops involving Canada COM personnel (i.e., a CBRN advisor plus medical and FD staff) and CBRN advisors from stakeholder organizations (i.e., the Canadian Army, Royal Canadian Navy, Royal Canadian Air Force, Canadian Special Operations Command, and the Strategic Joint Staff).

We used a purpose-built spreadsheet-based tool with embedded Microsoft Visual Basic for Applications code throughout the task analysis. During the workshops, we projected the tool's data input interface onto a screen, to inform and foster participants' discussions. An analogue of the data input interface for the notional task and vignette sets is presented in Figure 4. There, each row corresponds to a notional vignette and each column pertains to a notional task. During the workshop, participants considered each potential task in turn. For each task, they first openly discussed then estimated (on a consensus basis) the probability of the CAF receiving a performance request within the context of each vignette individually. Each likelihood estimate was entered into the interface, at the intersection of the applicable vignette's row and task's column. Estimates were made quantitatively, based on a colour-coded, seven-interval scale (Figure 4) with extrema of 0% (i.e., "never" or "not applicable") and 100% (i.e., "always"). The intervening likelihood range was equipartitioned into five intervals, i.e.,

- greater than 0% to 20% (i.e., "very improbable"),
- 20% to 40% (i.e., "improbable"),
- 40% to 60% (i.e., "as likely as not"),
- 60% to 80% (i.e., "probable"), and
- 80% to less than 100% (i.e., "very probable").

Though an interval scale is less precise than point estimates, its use was required to facilitate the attainment of consensus concerning 648 (i.e., 54 potential tasks × 12 vignettes) likelihood estimates during the time-limited workshops.

For illustrative purposes, we randomly generated the performance request likelihoods for the notional task set presented in Figure 4.[8]

[8] When generating each coloured cell in Figure 4, we assigned a 50% chance of selecting the 0% task performance request likelihood interval (i.e., grey; "never" or "not applicable") and equal chances of

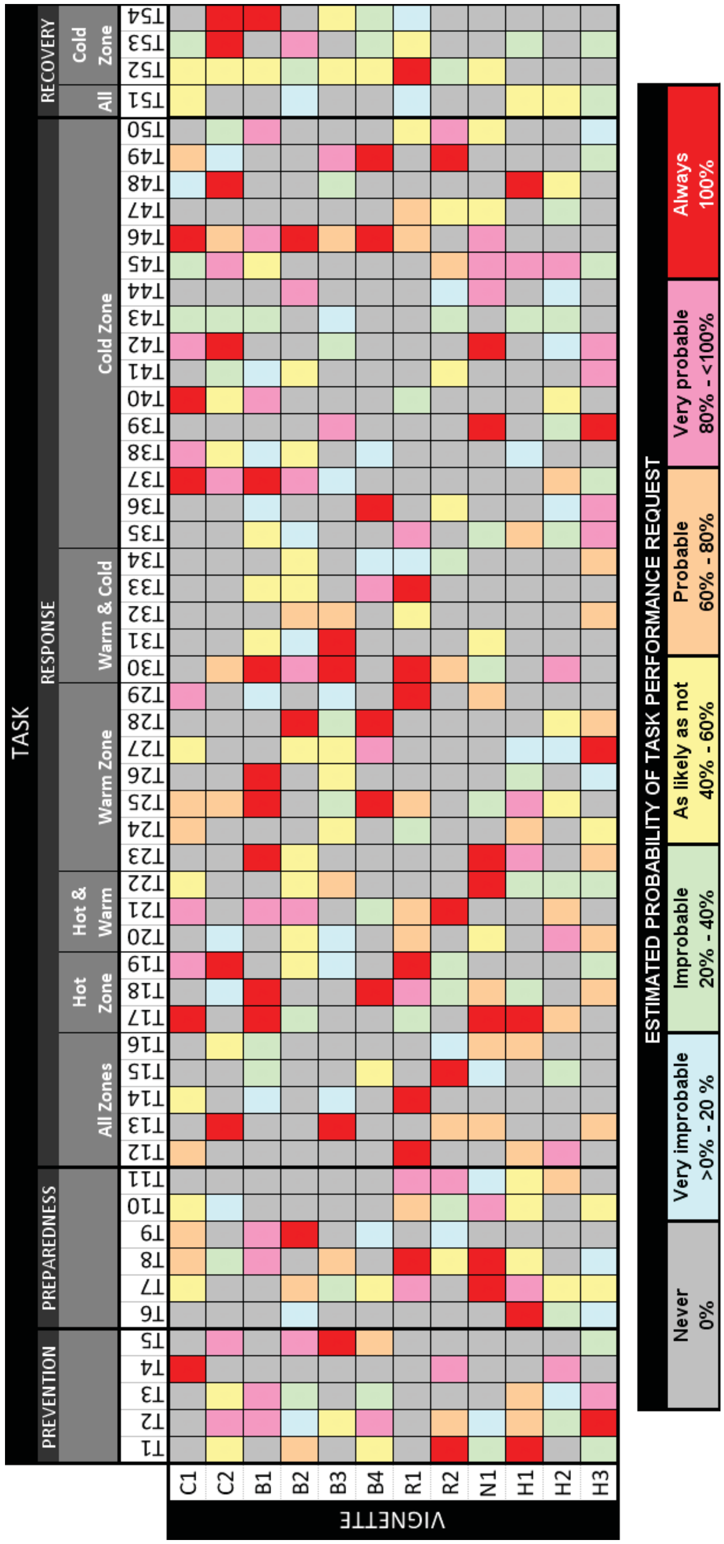

Figure 4: Notional task performance request probabilities by vignette.

$0.5/6 \cong 8.3\%$ for selecting each of the other six intervals. This arbitrary asymmetry crudely reflects the reality that many potential tasks would not be applicable to a given vignette.

3.4 Aggregation of task performance request probabilities

We accounted for the large variation in relative vignette likelihoods (Figure 3; Table 5) and the strong situational dependence of task performance request probabilities (Figure 4) by combining the two data sets, as follows. In so doing, we obtain the vignette-weighted probabilities of receiving performance requests for particular tasks, given a domestic CBRN event. Each such probability is an estimate of how likely the CAF would be to receive a performance request for a specific task, should a domestic CBRN event occur.

We denote each of the 648 task performance request likelihoods presented in Figure 4 using the notation $p_{Tj}^{(ai)}$. Here, the subscript *Tj* corresponds to a particular task and the superscript *ai* pertains to the *i*th vignette involving agent class *a*, within which the probability of a performance request was estimated. Thus, for example, $p_{T16}^{(B1)}$ denotes the estimated probability of the CAF receiving a request to perform task T16, within the context of the first biological vignette, B1.

We denote the estimated probability of the CAF being requested to perform a particular task *Tj* in relation to a domestic CBRN event by P_{Tj}. Such values are readily calculated as a weighted sum, involving the relative vignette probabilities P_{ai} (Figure 3; Table 5) and the vignette-specific task performance request likelihoods $p_{Tj}^{(ai)}$ (Figure 4), as follows:

$$P_{Tj} = \sum_{ai} P_{ai} \, p_{Tj}^{(ai)} \ . \tag{29}$$

So, for example, the estimated probability of the CAF being requested to perform task T16 in response to a domestic CBRN event is given by:

$$\begin{aligned} P_{T16} &= P_{C1}p_{T16}^{(C1)} + P_{C2}p_{T16}^{(C2)} + P_{B1}p_{T16}^{(B1)} + P_{B2}p_{T16}^{(B2)} + P_{B3}p_{T16}^{(B3)} + P_{B4}p_{T16}^{(B4)} \\ &\quad + P_{R1}p_{T16}^{(R1)} + P_{R2}p_{T16}^{(R2)} + P_{N1}p_{T16}^{(N1)} + P_{H1}p_{T16}^{(H1)} + P_{H2}p_{T16}^{(H2)} + P_{H3}p_{T1}^{(H3)}. \end{aligned} \tag{30}$$

From Figure 4, $p_{T16}^{(C1)} = p_{T16}^{(B2)} = p_{T16}^{(B3)} = p_{T16}^{(B4)} = p_{T16}^{(R1)} = p_{T16}^{(H2)} = p_{T16}^{(H3)} = 0$, so the equation above reduces to:

$$P_{T16} = P_{C2}p_{T16}^{(C2)} + P_{B1}p_{T16}^{(B1)} + P_{R2}p_{T16}^{(R2)} + P_{N1}p_{T16}^{(N1)} + P_{H1}p_{T16}^{(H1)}. \tag{31}$$

Substituting the vignette probabilities P_{ai} from Table 5 and the midpoints of the intervals in Figure 4 for the vignette-specific task performance request probabilities $p_{Tj}^{(ai)}$ yields:

$$\begin{aligned} P_{T16} &= 0.0020(0.5) + 0.0143(0.3) + 0.2552(0.1) + 0.1860(0.7) + 0.0005(0.7) \\ &= 0.16 \end{aligned} \tag{32}$$

Thus, the notional probability that the CAF would be requested to perform task T16 following a domestic CBRN event is $P_{T16} \cong 16\%$.

3.5 Visualization of aggregated probabilities, P_{Tj}

For all tasks within the notional set, vignette-weighted performance request probabilities P_{Tj} in relation to a domestic CBRN event are plotted in Figure 5 and grouped by temporal phase there. Within each phase, the tasks have been sorted in descending order of performance request likelihood.

Figure 5's vignette-weighted task performance request probabilities P_{Tj} are strongly affected by the wide range spanned by the estimated vignette probabilities P_{ai} (Figure 3; Table 5). For instance, the five most probable of the twelve notional vignettes (i.e., B3, R1, R2, N1, and H2) collectively represent ~92% of potential domestic CBRN events. Thus, tasks with sizeable performance request likelihoods for such vignettes (i.e., $p_{Tj}^{(B3)}$, $p_{Tj}^{(R1)}$, $p_{Tj}^{(R2)}$, $p_{Tj}^{(N1)}$, and $p_{Tj}^{(H2)}$; Figure 4) will have relatively large vignette-weighted performance request probabilities P_{Tj}. For example, task T30 has sizeable performance request likelihoods in each of the five most probable vignettes (i.e., $p_{T30}^{(B3)} = 1$, $p_{T30}^{(R1)} = 1$, $p_{T30}^{(R2)} = 0.7$, $p_{T30}^{(N1)} = 0.3$, and $p_{T30}^{(H2)} = 0.9$; Figure 4). Consequently, its vignette-weighted performance request probability $T_{30} \cong 74\%$ is not only large, it is the largest. Conversely, the four least probable notional vignettes (i.e., C1, C2, B4, and H1) collectively represent just ~0.7% of potential domestic CBRN events. As a result, they contribute negligibly to the vignette-weighted task performance request probabilities P_{Tj} depicted in Figure 5.

Figure 5's vignette-weighted task performance request probabilities also span a broad range. For example, whereas notional requests for the performance of task T30 are expected after nearly three-quarters of domestic CBRN events, performance requests for T38 are only anticipated in ~2% of such cases. For most tasks, the notional likelihood of a performance request in relation to a domestic CBRN event is in the 10%-40% range.

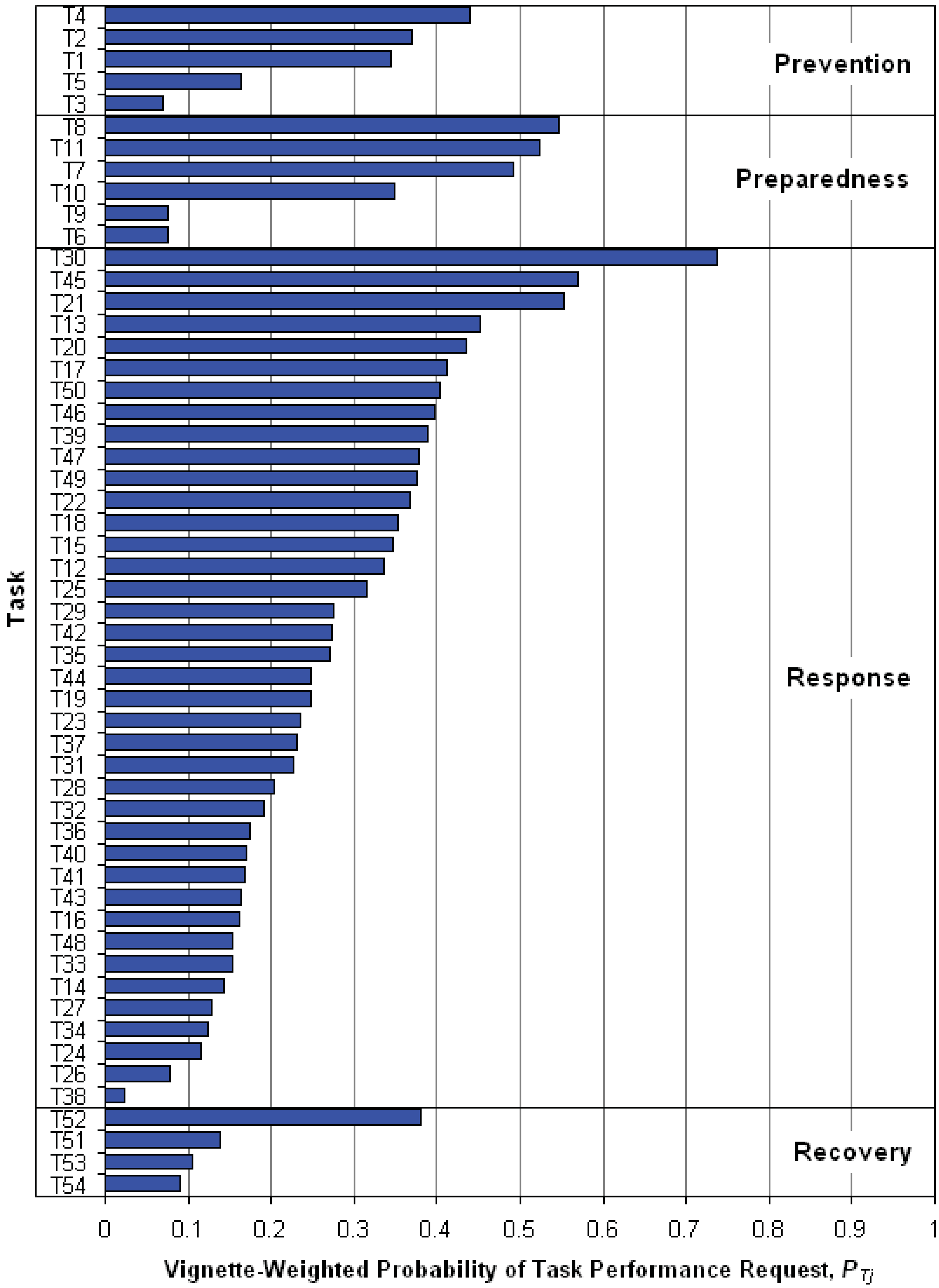

Figure 5: Performance request probabilities for tasks within the notional set, in relation to a domestic CBRN event.

3.6 Discussion

The task analysis method and results were embraced by Canada COM/CJOC planners and decision makers alike. The method's systematic elicitation and aggregation of several hundred subjective judgements encompassing a diversity of situations imposed valuable structure on a complex planning problem.

Even in isolation (without regard to vignette likelihoods), Canada COM/CJOC planners considered the real-world analogue of Figure 4 to be valuable because:

- it offered an expansive framework for considering the diverse circumstances in which the CAF may be requested to perform various tasks;
- it depicted the multitude of estimates graphically, in a concise and intuitive manner that fostered stakeholder discussions;
- it readily enabled the identification of tasks for which performance requests were very unlikely to be received within most or any of the vignettes; and, conversely,
- it readily enabled the identification of tasks for which performance requests were very likely to be received within most or all of the vignettes.

Canada COM/CJOC planners also highly valued the real-world analogue of Figure 5. The figure, which similarly depicts vignette-weighted task performance request probabilities in a sorted fashion, was deemed very useful because it simplifies planning and decision making, by taking into account diverse vignette likelihoods. Furthermore, it clearly and concisely presents aggregated estimates of what the CAF may be requested to do, in relation to a domestic CBRN event.

Like the vignette analysis, the task analysis (as it was applied during Canada COM/CJOC concept development) has some limitations. First, the 648 consensus estimates of vignette-specific task performance request likelihoods (Figure 4) were obtained systematically from workshop participants, but in a manner which lacked anonymity. Though, in principle, alternative elicitation means could have been used to achieve anonymity of opinion, their application presumably would have been infeasible, given the large number of estimates required and the workshops' time-limited nature.

Second, the associated uncertainties were not elicited for the estimated vignette-specific task performance request likelihoods (Figure 4). Though such uncertainties would have been analytically valuable, workshop durations would have been insufficient for participants to achieve consensus regarding so many uncertainties.

4 Requirement analysis

In regards to a potential domestic CBRN event, vignette analysis provides estimated likelihoods for what might occur, whereas task analysis yields probability estimates of what the CAF may be requested to do. Requirement analysis, the third component of the VITRO approach supporting concept development, involves estimating force employment requirements for tasks that the CAF may be requested to perform.

During the Canada COM/CJOC concept development work, we categorized force employment requirements in terms of personnel and equipment. However, we deferred the estimation of equipment requirements, because:

1. they were beyond the scope of the Canada COM/CJOC concept development effort and

2. the quantities of equipment required depend on whether items are issued to individual personnel, held at a central depot, or pre-positioned at various locations. Decisions concerning equipment allocation would not be taken during a concept's development, but rather during subsequent contingency planning. Thus, it was reasonable to defer consideration of equipment requirements until the contingency planning stage.

4.1 Set of individual training levels

To address personnel requirements, we specified a set of six individual training levels, as defined in Table 6. For exactness during the Canada COM/CJOC requirement analysis, the IS1, IS2, and IS3 training levels were named and defined to correspond precisely to the "individual standards" set out in the "Perform CBRN Defence" appendix to the CAF's Individual Battle Task Standards for Land Operations document [21].

Table 6: Definitions of individual training levels used during requirement and option analyses.

Training Level	Short Form τ	Description
General Duty	GD	Military personnel who have not received any CBRN defence training
IS1-trained	IS1	Military personnel who have received basic CBRN defence training, to enable their survival in a CBRN environment
IS2-trained	IS2	Military personnel who have received IS1 training plus additional instruction, to enable them to operate in a CBRN environment
IS3-trained	IS3	Military personnel who have received IS2 training plus further instruction, to enable them to perform specialized tasks in a CBRN environment
CBRN Specialist	CS	Military personnel who have received additional, advanced CBRN defence training from the Canadian Forces Fire and CBRN Academy or foreign equivalent
Non-CBRN Specialist	NCS	Military or civilian experts in fields other than CBRN defence, e.g., scientists, logisticians, medical personnel, etc.

4.2 Vignette and task sets

The Canada COM/CJOC requirement analysis employed the real-world vignette and task sets described in Sections 2.1.1 and 3.1, respectively. A CJOC CBRN advisor and a FD cell member jointly estimated the number of personnel that would be required, at each training level, to perform each task "adequately", within the context of each vignette. For analytical purposes, we defined "adequate" task performance as the minimum acceptable level in each situation. Admittedly, "adequate" levels of task performance can vary by agent type, agent quantity, agent quality, dissemination means, event location, event scale, event duration, civilian response capabilities/capacities, etc. We sought to account for such diversity (at least partly) by estimating personnel requirements on a vignette-by-vignette basis. Nevertheless, when estimating such requirements, CJOC personnel were required to make numerous subjective judgements.

4.3 Requirements estimation

CJOC personnel entered their requirements estimates into six tabs of a spreadsheet-based tool that we developed. Each tab was associated with a particular training level and contained a matrix analogous to that depicted in Figure 6. That figure depicts fictitious general duty personnel requirements for the notional vignette and task sets described in Sections 2.1.2 and 3.1, respectively. Analogous notional estimates for CBRN specialists are presented in Figure 7, whereas those for the remaining four individual training levels are represented in Annex C.

CJOC personnel considered each task in turn when estimating requirements. For a given task *Tj*, they entered estimated quantities of personnel $r_{Tj,\tau}^{(ai)}$ required at each training level τ for adequate performance within each vignette *ai* on the corresponding tabs.[9,10] For example, using this notation, $r_{T4,GD}^{(C1)}$ denotes the estimated quantity of general duty personnel required to perform task T4 adequately within chemical vignette C1. To avoid unnecessary work, CJOC staff did not estimate personnel requirements for task-vignette pairs for which the likelihood of receiving a performance request was estimated to be zero during the task analysis (i.e., where $p_{Tj}^{(ai)} = 0$; Figure 4). Such cells are shaded grey in Figure 4, Figure 6, and Figure 7.

Annex C describes how we generated the notional set of personnel requirements $r_{Tj,\tau}^{(ai)}$ that we use to illustrate the option analysis method in this report. The key points are as follows:

1. For each task-vignette pair, the quantities of personnel required at each training level $r_{Tj,\tau}^{(ai)}$ were randomly determined based on probability distributions that we have chosen arbitrarily, for illustrative purposes. Consequently, the notional set's personnel requirements for performing a given task are not correlated across different vignettes. Though a degree of correlation exists in the Canada COM/CJOC requirements set, it is not needed to illustrate the requirement analysis method here.

2. For convenience when quantifying non-specialist personnel, we arbitrarily chose to use five discrete personnel quantities per training level in the notional requirements set. During the Canada COM/CJOC requirement analysis, discrete manning levels were not used. Rather, CJOC personnel estimated the required personnel quantity for each task-vignette pair as precisely as possible.

For specialist personnel, CJOC personnel estimated required personnel quantities as precisely as possible, for each task-vignette pair. However, the wide range of specialist types potentially complicated the Canada COM/CJOC option analysis, so a simplifying assumption was made (as discussed in Section 5). When generating the notional set of specialist personnel requirements (Figure 7 and Figure C-4), we also adopted a simplified approach. That is, we randomly determined for each task-vignette pair whether specialist personnel were required or not. This was done independently for CBRN specialists and non-CBRN specialists. This simplified approach suffices to illustrate both the requirement and option analysis methods.

[9] Table 6's "short form" column lists the possible values of τ based on this notation.
[10] Here, as in the vignette and task analyses, *ai* denotes the *i*th vignette involving agent class *a*.

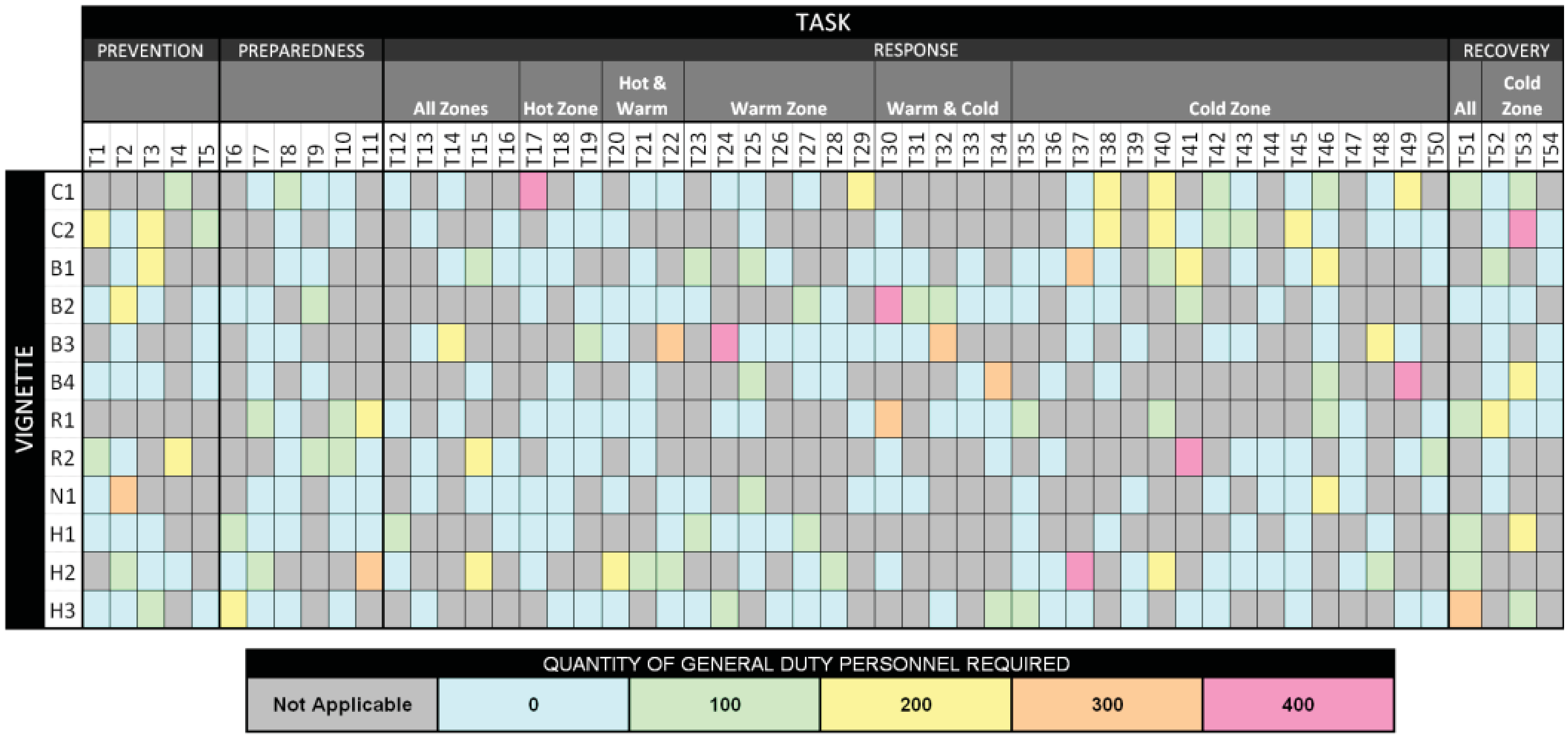

Figure 6: Notional quantities of general duty personnel required to perform each task adequately within each vignette.

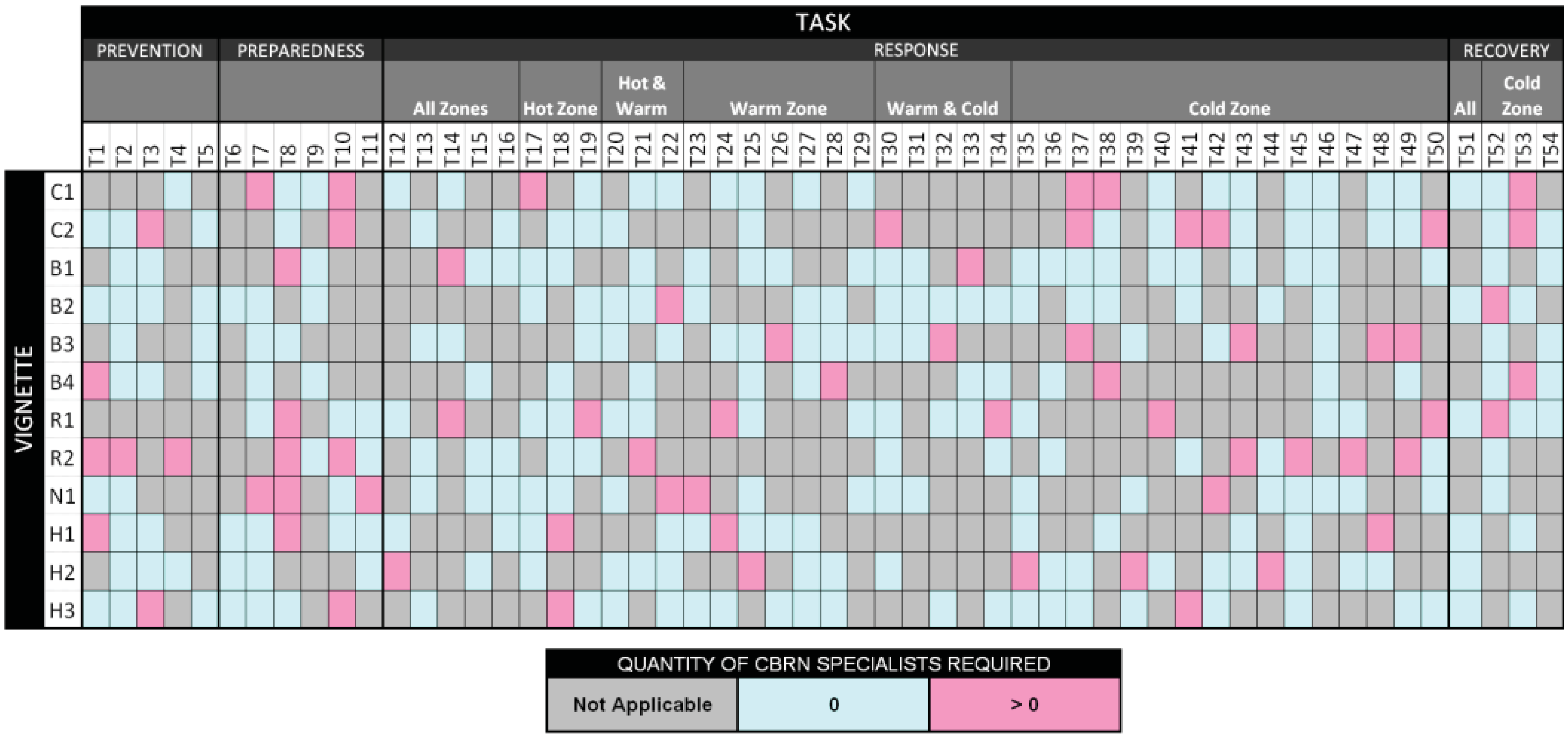

Figure 7: Notional quantities of CBRN specialists required to perform each task adequately within each vignette.

4.4 Discussion

Though relatively straightforward, the requirement analysis method advanced the Canada COM/CJOC concept development effort in three respects.

1. The method systematically reduced the considerable complexity of the requirements estimation problem, by leading staff members to consider the personnel requirements for each task-vignette pair individually.

2. The estimates' detail and structured presentation facilitate external review. Such transparency is not a universal property of other estimation methods.

3. The task and requirement analyses' results were fully compatible, since both methods involved estimates for individual task-vignette pairs. Such compatibility was exploited during the Canada COM/CJOC option analysis (Section 5), to which the results of the task and requirement analyses were inputs.

The requirement analysis, as it was applied during Canada COM/CJOC concept development, involved a number of limitations:

- Though personnel requirements were estimated as a function of individual training levels, collective training needs were not considered. The requirements for and ability to deliver necessary collective training were left as questions to be addressed during future, detailed planning.

- As discussed in the introduction to Section 4, the estimation of equipment requirements was deferred.

- All requirements estimates were subjective, since they manifested the professional opinions of Canada COM/CJOC personnel. Some estimates could potentially be refined through exercises or experimentation. However, the enormous amount of effort required to empirically validate requirement estimates for every task-vignette pair would almost certainly be prohibitive. Consequently, some degree of subjectivity in estimating such requirements is presumably inevitable.

- The Canada COM/CJOC set of estimated personnel requirements was necessarily uncertain, due to the rarity and potential real-world variability of the vignettes considered, as well as the estimators' finite knowledge. One way to address this limitation might have been to elicit inputs as three-point estimates (i.e., estimates of minimum, most likely, and maximum requirements for adequate response) rather than as single-point estimates. However, this approach would have significantly increased the elicitation time, which was not feasible during Canada COM/CJOC's concept development. It also would have significantly increased the complexity of the analysis and associated spreadsheet tools (although methods like Monte Carlo sampling or fuzzy arithmetic exist to combine three-point estimates). This increased complexity would likely have reduced the transparency of the approach and the clarity of the results, and there was no guarantee that the epistemic uncertainties surrounding the estimates would have been captured.

5 Option analysis

In a resource-constrained environment, concept developers generally strive to identify cost-effective options, i.e., those which deliver necessary capabilities via relatively modest resource commitments. However, assessing options' cost-effectiveness systematically in a valid, transparent, and defensible manner can be challenging – particularly for complex endeavours such as domestic CBRN event response. Nevertheless, the quality of an option analysis can be a key factor which affects not only a concept's fitness for purpose, but also its ultimate acceptance or rejection by decision makers and stakeholders. Thus, despite the challenges involved, concept developers and analysts alike must ensure that their option analysis approach is of a high quality and well suited to the planning problem at hand.

To support the Canada COM/CJOC concept development effort, we devised an option analysis method to evaluate the CBRN event response capabilities associated with various potential resource commitments. In so doing, we built upon the results of the vignette, task, and requirement analyses described previously in this report. Strictly speaking, we did not perform a cost-effectiveness analysis, which typically would be framed in monetary terms.[11] Rather, our method quantified potential trade-offs between commitments of various quantities of personnel, their levels of individual training, and their corresponding capability gaps.

5.1 Force packages

During the Canada COM/CJOC concept development effort, we introduced notional "force packages", which served as "options" during the option analysis. By comparing such force packages with estimated personnel requirements, we could identify and better understand potential capability gaps.

Each force package specifies quantities of personnel at particular training levels, e.g., 200 IS1-trained plus 100 IS2-trained personnel. As such, a force package does not represent a course of action (COA) for concept development per se, since it does not specify details concerning unit structure(s), basing, rotations, etc. Rather, a force package may represent a starting point for COA creation during the development of a future domestic CBRN response CONPLAN.

During the Canada COM/CJOC work, we reduced the infinite number of potential force packages to an analytically tractable quantity in the two following ways.

1. We identified thresholds that occurred frequently in the estimated personnel requirements at the general duty, IS1, IS2, and IS3 training levels and limited force packages to combinations of those personnel quantities.

[11] Though not conducted, a cost-effectiveness analysis could be performed by extending the VITRO approach described in this report with a risk analysis and a costing of military resources. Such a risk analysis would aggregate the existing vignette (i.e., likelihood) analysis results with those of a consequence assessment for each vignette. DRDC's operational analysis community and its international partners are currently pursuing the development of simultaneously valid and feasible CBRN risk assessment methods.

2. We limited force package compositions to include either no specialists whatsoever or quantities of CBRN and non-CBRN specialists that would suffice for any potential task. This restriction greatly reduced the number of potential force packages, given the diversity of specialist types.

To illustrate the option analysis method, we employ a set of notional force packages which differ from those used in the Canada COM/CJOC analysis. We let $q_{f,\tau}$ denote the quantity of personnel of individual training level τ associated with a given force package *f*. We define ten force packages labelled A through J, with compositions as described in Table 7. To highlight training-related differences, force packages A-F each consist of 500 non-specialist personnel, whose aggregate level of training increases from left to right in Table 7. To illustrate capacity-related differences, force packages G-J each consist of twice as many (i.e., 1000) non-specialist personnel, whose training level also increases from left to right in the table. We assessed each force package twice, assuming different quantities of specialists in each instance. That is, we assumed (a) that quantities of specialists sufficient to perform any task were included initially, then, (b) that no specialists were included, during the second assessment. This collective, "all or nothing" approach to specialists enables us to highlight economically their notional importance to responses to domestic CBRN events.

Table 7: Personnel quantities by training level comprising notional force packages A-J. Specialist quantities denoted by † were collectively assumed to be either zero or sufficient for performing any task, depending on the assessment conducted.

Training Level	Force Package									
	A	B	C	D	E	F	G	H	I	J
General Duty	500	300	0	0	0	0	1000	0	0	0
IS1	0	200	500	300	0	0	0	1000	0	0
IS2	0	0	0	200	500	300	0	0	1000	600
IS3	0	0	0	0	0	200	0	0	0	400
CBRN Specialist	†	†	†	†	†	†	†	†	†	†
Non-CBRN Specialist	†	†	†	†	†	†	†	†	†	†

The notional force packages of Table 7 represent various combinations of personnel quantities and training levels. Next, we calculate the gap probabilities associated with each force package, by considering them in conjunction with the results of the vignette, task, and requirement analyses described previously.

5.2 Calculation of gap probabilities

To provide a basis for option comparisons, we calculate the probability that a given force package would be unable to fulfill a particular task performance request adequately, given a domestic CBRN event. To obtain such task-specific gap probabilities for each force package, we must first calculate and aggregate the intermediate quantities presented in the following subsections.

5.2.1 Gap probabilities by task-vignette pair and training level, $\gamma_{f,Tj,\tau}^{(ai)}$

We begin by considering, in turn, each task *Tj* within the context of each vignette *ai*. Our aim is to determine whether the personnel requirement $r_{Tj,\tau}^{(ai)}$ at a given training level τ exceeds the available quantity of qualified personnel $Q_{f,\tau}$ within a particular force package *f*. If so, a performance gap will exist, and we will assign a training level-specific gap probability value $\gamma_{f,Tj,\tau}^{(ai)}$ of unity for the force package's task-vignette pair. Otherwise, the personnel requirement can be met, so we will assign a training level-specific gap probability $\gamma_{f,Tj,\tau}^{(ai)}$ value of zero. In formal terms, the training level-specific gap probability $\gamma_{f,Tj,\tau}^{(ai)}$ for a given training level τ can be expressed in terms of the quantity of available qualified personnel $Q_{f,\tau}$ as:

$$\gamma_{f,Tj,\tau}^{(ai)} = \begin{cases} 1 & if\ r_{Tj,\tau}^{(ai)} > Q_{f,\tau}, \\ 0 & otherwise. \end{cases} \tag{33}$$

When determining available quantities of qualified personnel within a force package $Q_{f,\tau}$, we note that the non-specialist individual training levels described in Table 6 are not mutually exclusive. Rather, some training levels are prerequisites for others. For example, the general duty, IS1, and IS2 training levels are prerequisites for IS3-level training. So, an available IS3-trained person can be employed to fulfill an IS2-, IS1-, or general duty-level requirement. Thus, when determining training level-specific gap probabilities $\gamma_{f,Tj,\tau}^{(ai)}$, the available quantity of qualified personnel $Q_{f,\tau}$ within a force package *f* able to fulfill a τ-level personnel requirement includes both

a. the force package's quantity of personnel who have been trained to level τ as well as

b. more highly trained personnel who have not been allocated in fulfillment of another personnel requirement.

Based on this understanding of non-specialist training levels' cumulative nature, we can form expressions for each training level-specific gap probability $\gamma_{f,Tj,\tau}^{(ai)}$. To meet IS3-level personnel requirements, only IS3-trained personnel will suffice, i.e., $Q_{f,IS3} = q_{f,IS3}$. Thus, from Equation (34), the IS3 training level-specific gap probability $\gamma^{(ai)}_{f,Tj,IS3}$ is given by:

$$\gamma^{(ai)}_{f,Tj,IS3} = \begin{cases} 1 & if \;\; r^{(ai)}_{Tj,IS3} > q_{f,IS3}, \\ 0 & otherwise. \end{cases} \tag{34}$$

The quantity of IS3-trained personnel that remain available to satisfy IS2-level (or lower) personnel requirements depends on how many personnel (if any) were required to satisfy the IS3-level requirement. If the IS3-level requirement could not be satisfied, then all IS3-trained personnel $q_{f,IS3}$ would remain available.[12] Alternatively, if the IS3-level requirement was satisfied, then the quantity of IS3-trained personnel who remain available is given by the difference of the initial quantity and the number allocated to meet the requirement, i.e., $q_{f,IS3} - r^{(ai)}_{Tj,IS3}$. Given these two possible situations, the quantity of available personnel qualified to satisfy IS2-level requirements $Q_{f,IS2}$ can be expressed as:

$$Q_{f,IS2} = \begin{cases} q_{f,IS2} + q_{f,IS3} & if \; \gamma^{(ai)}_{f,Tj,IS3} = 1, \\ q_{f,IS2} + \left(q_{f,IS3} - r^{(ai)}_{Tj,IS3}\right) & if \; \gamma^{(ai)}_{f,Tj,IS3} = 0. \end{cases} \tag{35}$$

This relationship can be generalized as follows, to yield the available quantity of qualified non-specialist personnel $Q_{f,\tau}$ able to satisfy a τ-level personnel requirement:

$$Q_{f,\tau} = \begin{cases} q_{f,\tau} + q_{f,\tau+1} & if \; \gamma^{(ai)}_{f,Tj,\tau+1} = 1, \\ q_{f,\tau} + \left(q_{f,\tau+1} - r^{(ai)}_{Tj,\tau+1}\right) & if \; \gamma^{(ai)}_{f,Tj,\tau+1} = 0. \end{cases} \tag{36}$$

We can apply Equations (33) and (36) iteratively, to obtain training level-specific gap probabilities $\gamma^{(ai)}_{f,Tj,\tau}$ for the remaining IS2, IS1, and general duty levels, in the following manner:

1. We obtain $\gamma^{(ai)}_{f,Tj,IS2}$ via Equation (33), by setting $\tau = IS2$ and substituting the result for $Q_{f,IS2}$ given by Equation (35).

2. We then calculate the available quantity of qualified personnel able to satisfy IS1-level requirements $Q_{f,IS1}$, by setting $\tau = IS1$ in Equation (36).

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[12] Here, we have assumed that personnel would not be allocated in vain, when their numbers are insufficient to satisfy a training level-specific requirement.

3. Using that result, we obtain $\gamma^{(ai)}_{f,Tj,IS1}$ via Equation (33), by setting $\tau = IS1$.

4. Next, we calculate the available quantity of qualified personnel who can fulfill general duty-level requirements $Q_{f,GD}$, by setting $\tau = GD$ in Equation (36).

5. Finally, we use that result to determine $\gamma^{(ai)}_{f,Tj,GD}$ via Equation (33), by setting $\tau = GD$.

Thus far in this section, we have discussed the means by which training-level specific gap probabilities can be obtained for the non-specialist members of a force package. For specialist members, we now define the analogous training level-specific gap probabilities $\gamma^{(ai)}_{f,Tj,CS}$ (for CBRN specialists) and $\gamma^{(ai)}_{f,Tj,NCS}$ (for non-CBRN specialists). As discussed in Section 5.1, during the Canada COM/CJOC option analysis, we assumed that force packages included either (a) sufficient quantities of both specialist types to perform all requested tasks adequately or (b) no specialists of either kind. In the first (i.e., "sufficient specialists") case, the associated training level-specific gap probabilities for a given force package *f* were always zero, i.e., $\gamma^{(ai)}_{f,Tj,CS} = \gamma^{(ai)}_{f,Tj,NCS} = 0$ for any task *Tj* performed in any vignette *ai*. In the "no-specialists" case, $\gamma^{(ai)}_{f,Tj,CS} = \gamma^{(ai)}_{f,Tj,NCS} = 0$ only when specialists were not required to perform a task *Tj* within vignette *ai*. Otherwise, $\gamma^{(ai)}_{f,Tj,CS} = 1$ when CBRN specialists were required and $\gamma^{(ai)}_{f,Tj,NCS} = 1$ when non-CBRN specialists were necessary.

In practice, the determination of training level-specific gap probabilities is relatively straightforward. We illustrate the process via the following notional example, whose values are summarized in Table 8. Consider force package B (Table 7), which consists of 200 IS1-trained and 300 general-duty personnel (i.e., $q_{B,IS1} = 200$, $q_{B,GD} = 300$) plus "sufficient" quantities of both CBRN and non-CBRN specialists. Next, let force package B be requested to perform task T30 in the context of vignette B2. For that task-vignette pair, the quantity of personnel required at each training level (Figure 6, Figure 7, and Figure C-1 to Figure C-4) is listed in Table 8. Since the force package does not contain any IS3-trained members, it cannot satisfy the IS3 training level requirement of $r^{(B2)}_{T30,IS3} = 25$ personnel. Consequently, the IS3 training level-specific gap probability is $\gamma^{(B2)}_{B,T30,IS3} = 1$. Since no IS2-trained or IS1-trained personnel are required, the corresponding training level-specific gap probabilities are $\gamma^{(B2)}_{B,T30,IS2} = 0$ and $\gamma^{(B2)}_{B,T30,IS1} = 0$. Since there is no personnel requirement at the IS1 training level, all of the force package's 200 IS1-trained members remain available for allocation. The task-vignette pair's general-duty requirement is $r^{(B2)}_{T30,GD} = 400$ personnel. Since this requirement can be met by allocating all of the force package's 300 general-duty personnel plus 100 of its unassigned IS1-trained members, the associated general-duty gap probability is $\gamma^{(B2)}_{B,T30,GD} = 0$. For CBRN specialists and non-CBRN specialists alike, the training level-specific gap probabilities are zero (i.e., $\gamma^{(B2)}_{B,T30,CS} = 0$ and $\gamma^{(B2)}_{B,T30,NCS} = 0$), since (a) no specialists of either type are required and (b) the force package was assumed to incorporate sufficient quantities of both specialist types.

Table 8: Summary of notional values used to illustrate the determination of training level-specific gap probabilities.

Training Level, τ	Quantity of Personnel in Force Package	Quantity of Personnel Required	Force Package Personnel Allocated	Gap Probability by Training Level
GD	$q_{B,GD} = 300$	$r^{(B2)}_{T30,GD} = 400$	GD: 300 personnel IS1: 100 personnel	$\gamma^{(B2)}_{B,T30,GD} = 0$
IS1	$q_{B,IS1} = 200$	$r^{(B2)}_{T30,IS1} = 0$	None required	$\gamma^{(B2)}_{B,T30,IS1} = 0$
IS2	$q_{B,IS2} = 0$	$r^{(B2)}_{T30,IS2} = 0$	None required	$\gamma^{(B2)}_{B,T30,IS2} = 0$
IS3	$q_{B,IS3} = 0$	$r^{(B2)}_{T30,IS3} = 25$	IS3: None available	$\gamma^{(B2)}_{B,T30,IS3} = 1$
CS	$q_{B,CS} = sufficient$	$r^{(B2)}_{T30,CS} = 0$	None required	$\gamma^{(B2)}_{B,T30,CS} = 0$
NCS	$q_{B,NCS} = sufficient$	$r^{(B2)}_{T30,NCS} = 0$	None required	$\gamma^{(B2)}_{B,T30,NCS} = 0$

In the preceding example, training level-specific gap probabilities were determined for notional force package B, for a specific task-vignette pair (i.e., task $Tj = T30$ and vignette $ai = B2$). During an option analysis, the procedure would be repeated for all task-vignette pairs, for each force package in turn. During the Canada COM/CJOC option analysis, we used a spreadsheet-based tool to make such determinations and to store the resulting gap probabilities. To further illustrate our method, we have used such a tool to calculate force package B's training level-specific gap probabilities $\gamma^{(ai)}_{B,Tj,\tau}$ for every task-vignette pair in our notional data set. Such results are presented in Annex D.

5.2.2 Gap probabilities by task-vignette pair, $g^{(ai)}_{f,Tj}$

In the previous section, we described means for determining training level-specific gap probabilities $\gamma^{(ai)}_{f,Tj,\tau}$ for a force package *f* that is requested to perform a task *Tj* in the context of vignette *ai*. We now describe the first step of a two-stage process for aggregating such data.

Specifically, we wish to determine the likelihood that a particular force package *f* will be unable to perform a requested task *Tj* adequately in the context of vignette *ai*. For convenience, we will refer to this likelihood as the force package's gap probability for a given task-vignette pair and denote it by $g^{(ai)}_{f,Tj}$. In conceptual terms, adequate task performance can only occur if a force package's composition satisfies the task-vignette pair's personnel requirements at every training level τ. Conversely, if any of the training-level specific personnel requirements cannot be met by the force package, then a performance gap will result. Thus, a force package's gap probability for a given task-vignette pair $g_{f,Tj}^{(ai)}$ can take on values of either zero or unity. It can be expressed formally in either of the two following manners:

$$g_{f,Tj}^{(ai)} = \begin{cases} 1 & if\ \gamma_{f,Tj,\tau}^{(ai)} = 1\ for\ any\ \tau \\ 0 & otherwise \end{cases}$$
$$or \qquad . \tag{37}$$
$$g_{f,Tj}^{(ai)} = 1 - \prod_{\tau} \left(1 - \gamma_{f,Tj,\tau}^{(ai)}\right)$$

Put a third way, we can obtain the gap probability for a given task-vignette pair $g_{f,Tj}^{(ai)}$ by applying a logical AND function to the associated binary-valued training level-specific gap probabilities $\gamma_{f,Tj,\tau}^{(ai)}$.

To illustrate this first aggregation step, we consider the tabulated values for the example presented in the previous section (Table 8). In that example, force package B does not meet the IS3-level personnel requirement for task T30 in vignette B2. Consequently, the associated IS3 training level-specific gap probability has a value of unity (i.e., $\gamma_{B,T30,IS3}^{(B2)} = 1$; Table 8). Since the tabulated training level-specific gap probabilities are not all zero-valued (i.e., since $\gamma_{B,T30,\tau}^{(B2)} = 0$ is not true for every training level τ), force package B would be unable to perform task T30 adequately in vignette B2. This performance gap is denoted by assigning a gap probability for the given task-vignette pair of $g_{B,T30}^{(B2)} = 1$.

During an option analysis, similar gap probability determinations would be made for every task-vignette pair, for each force package. During the Canada COM/CJOC option analysis, we used a spreadsheet-based tool to automate the evaluation process. For illustrative purposes, we have used such a tool to aggregate the notional training level-specific gap probabilities for force package B (i.e., $\gamma_{B,Tj,\tau}^{(ai)}$) that are discussed in Section 5.2.1 and tabulated in Annex D. Force package B's resulting gap probabilities as a function of task-vignette pair $g_{B,Tj}^{(ai)}$ are presented in Figure 8, where we have assumed that sufficient specialists are available.

In summary, for each force package considered as part of an option analysis, this first aggregation step collapses six matrices containing training level-specific gap probabilities $\gamma_{f,Tj,\tau}^{(ai)}$ into a single matrix of gap probabilities by task-vignette pair $g_{f,Tj}^{(ai)}$. In the context of this section's example involving force package B, the training-level specific data contained in Figure D-1 to Figure D-6 of Annex D were aggregated to yield Figure 8.

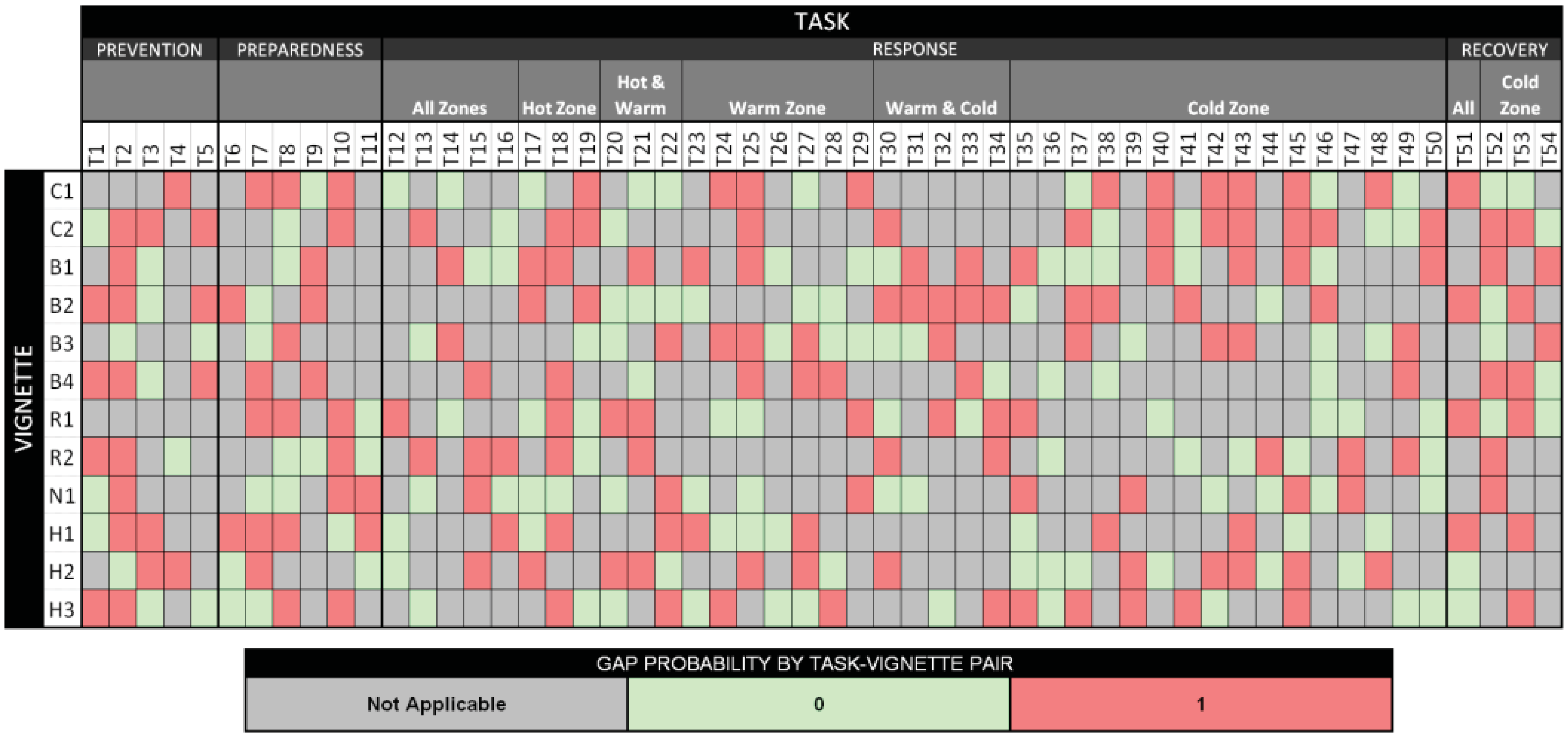

Figure 8: Notional gap probabilities by task vignette pair for force package B, assuming that sufficient specialists are available.

5.2.3 Gap probabilities by task, $G_{f,Tj}$

The first aggregation step of our option analysis approach yields force package-specific gap probabilities for task-vignette pairs $g_{f,Tj}^{(ai)}$ (such as those presented in Figure 8 for force package B). Such intermediate results are valuable to planners, since they illustrate how a force package's estimated ability to perform a given task adequately varies, based on the operational context (i.e, by vignette). However, to gauge a force package's ability to perform a given task with respect to the entire vignette set (i.e., in the general case), a further aggregation step is required. We now describe such a step, which involves weighted sums of gap probabilities for relevant task-vignette pairs $g_{f,Tj}^{(ai)}$. Our approach yields each force package's vignette-weighted gap probabilities for each potential task $G_{f,Tj}$, which constitute the final results of our option analysis method.

Given a domestic CBRN event, we derive the vignette-weighted gap probability $G_{f,Tj}$ (i.e., that a force package *f* would be unable to perform a requested task *Tj* adequately) as follows.

1. Given a domestic CBRN event, we assume that one of the vignettes *ai* in our set would approximate it. However, as discussed in Section 2.3, the set's vignettes are not equally probable (in general). Thus, during this second aggregation step, we must take into account the generally different probabilities of each vignette P_{ai}.

2. As discussed in Section 3.4, $p_{Tj}^{(ai)}$ denotes the likelihood that the performance of task *Tj* would be requested, given a particular vignette *ai*. As restated above, the likelihood of a particular vignette *ai*, given a domestic CBRN event is P_{ai}. Thus, the probability that a domestic CBRN event is approximated by vignette *ai* and involves a performance request for task *Tj* is given by the product $P_{ai}\, p_{Tj}^{(ai)}$.

3. From Section 5.2.2, $g_{f,Tj}^{(ai)}$ represents the likelihood that a force package *f* would be unable to perform task *Tj* adequately, when requested in the context of vignette *ai*. Thus, the product $P_{ai}\, p_{Tj}^{(ai)} g_{Tj}^{(ai)}$ represents the probability that a domestic CBRN event is approximated by vignette *ai* and involves a performance request for task *Tj* which force package *f* could not satisfy adequately.

4. We generalize the previous result (which pertains to a single vignette) by summing over all vignettes in the set. In so doing, we obtain each force package's vignette-weighted gap probabilities $G_{f,Tj}$, which apply to an arbitrary domestic CBRN event. These vignette-weighted gap probabilities $G_{f,Tj}$ each represent the expected likelihood that a force package *f* would be unable to perform adequately a requested task *Tj* in the context of an arbitrary domestic CBRN event. They represent the results of the second aggregation step and are given by:

$$G_{f,Tj} = \sum_{ai} P_{ai}\, p_{Tj}^{(ai)} g_{f,Tj}^{(ai)} \,. \tag{38}$$

Such vignette-weighted gap probabilities $G_{f,Tj}$ formed the basis for the Canada COM/CJOC option analysis concerning domestic CBRN event response. We now demonstrate how such gap probabilities are calculated, via an example which employs the notional data presented earlier in this report. To that end, we illustrate the calculation of $G_{B,T14}$, i.e., the probability that force package B would be unable to perform task T14 adequately, given a domestic CBRN event. For our chosen case, Equation (38) becomes:

$$G_{B,T14} = \sum_{ai} P_{ai}\, p_{T14}^{(ai)} g_{B,T14}^{(ai)} \,. \tag{39}$$

Next, we must gather the notional data required for each vignette *ai*. For task T14, the corresponding task performance request probabilities by vignette $p_{T14}^{(ai)}$ (Figure 4) are non-zero for only four vignettes, i.e., for $ai = \{C1, B1, B3, R1\}$. Thus, we need only consider these four vignettes during the calculation of $G_{B,T14}$. For such vignettes, we have tabulated the corresponding task performance request probabilities by vignette $p_{T14}^{(ai)}$ along with the corresponding vignette probabilities P_{ai} (Table 5; Figure 3) and task-specific gap probabilities $g_{B,T14}^{(ai)}$ (Figure 8) in Table 9.

Table 9: Notional data required to calculate the task-specific gap probability $G_{B,T14}$, assuming that sufficient specialists are available.

Vignette	**Vignette Probability**	**Mean Task Performance Request Probability**	**Task-Specific Gap Probability**
$ai = C1$	$P_{C1} = 0.0041$	$p_{T14}^{(C1)} = 0.5$	$g_{T14}^{(C1)} = 0$
$ai = B1$	$P_{B1} = 0.0143$	$p_{T14}^{(B1)} = 0.1$	$g_{T14}^{(B1)} = 1$
$ai = B3$	$P_{B3} = 0.1233$	$p_{T14}^{(B3)} = 0.1$	$g_{T14}^{(B3)} = 1$
$ai = R1$	$P_{R1} = 0.1276$	$p_{T14}^{(R1)} = 1$	$g_{T14}^{(R1)} = 0$

Having thus collected the required notional data, we substitute them into Equation (39) to complete the calculation:

$$G_{B,T14} = P_{C1}\, p_{T14}^{(C1)} g_{B,T14}^{(C1)} + P_{B1}\, p_{T14}^{(B1)} g_{B,T14}^{(B1)} + P_{B3}\, p_{T14}^{(B3)} g_{B,T14}^{(B3)} + P_{R1}\, p_{T14}^{(R1)} g_{B,T14}^{(R1)}$$

$$= (0.0041)(0.5)(0) + (0.0143)(0.1)(1) + (0.1233)(0.1)(1) + (0.1276)(1)(0) \qquad (40)$$

$$G_{B,T14} = 0.0138.$$

According to this result, given a domestic CBRN event, there is a ~1% likelihood that force package B would be requested to perform task T14 but unable to conduct it adequately.

5.3 Visualization of vignette-weighted gap probabilities, $G_{f,Tj}$

During an option analysis, the number of vignette-weighted gap probabilities $G_{f,Tj}$ under consideration can be large. For example, our notional data set involves ten force packages and 54 tasks, which give rise to $10 \times 54 = 540$ vignette-weighted gap probabilities. Consequently, effective means to visualize and facilitate the interpretation of such gap probabilities are important. In this section, we use notional data to illustrate means for visualizing vignette-weighted gap probabilities (a) for a particular force package and (b) for an ensemble of force packages.

For a single force package, vignette-weighted gap probabilities $G_{f,Tj}$ can be presented as in Figure 9 (which depicts notional data for force package B, given sufficient specialists). In the figure, we have grouped tasks by temporal phase. Within each phase, tasks are sorted according to their vignette-weighted gap probabilities, from highest to lowest. Such representations are readily interpreted. That is, given a domestic CBRN event, each bar denotes the likelihood that the given force package would be requested to perform a particular task but unable to conduct it adequately. For example, the figure indicates that, given a domestic CBRN event, the probability that force package B would be requested but unable to perform task T21 adequately is ~52%. Moreover, tasks whose gap probabilities exceed a threshold value can be identified immediately (e.g., in the figure, 12 response-phase tasks' gap probabilities are greater than ~20%).

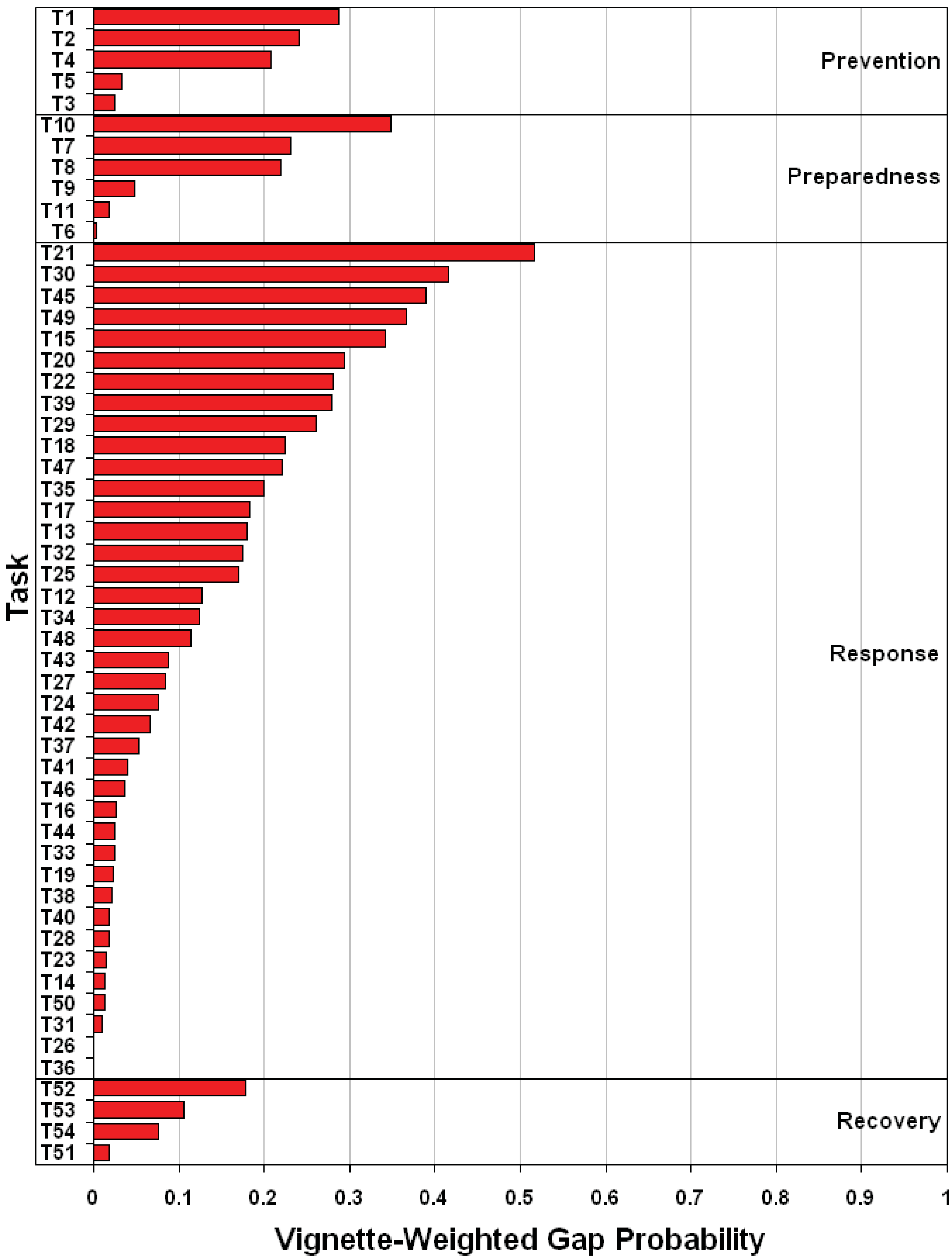

Figure 9: Vignette-weighted gap probabilities for force package B ($G_{B,Tj}$), assuming sufficient specialists, sorted within each temporal phase by probability.

To compare vignette-weighted gap probabilities across multiple force packages during the Canada COM/CJOC option analysis, we used a representation analogous to that shown in Figure 10. There, each column corresponds to a different force package (i.e., A through J), wherein white cells indicate the quantity of personnel at each training level. The quantities of specialists in each force package are not stated explicitly, but are assumed to be sufficient for any requested task. Each of the 54 notional tasks is represented by a row of coloured cells in the figure. Each cell's colour denotes the vignette-weighted gap probability $G_{f,Tj}$ of the associated force package-task combination.[13]

Using such a chart (Figure 10), we can explore trade-offs between quantities of personnel at various training levels and vignette-weighted gap probabilities for various tasks. As the quantities and/or degrees of training of personnel within a force package increase(s), vignette-weighted gap probabilities generally decrease, but not proportionally. We illustrate the nonlinearity of such trade-offs via the following two examples.

1. First, we compare force packages D (300 IS1-trained plus 200 IS2-trained personnel) and E (500 IS2-trained personnel). Though they each consist of 500 personnel, force package E's greater quantity of IS2-trained personnel makes it the more highly trained cadre. Yet, despite this training disparity, the force packages' notional vignette-weighted gap probabilities are quite similar for all tasks. Thus, the additional IS2-level training received by 300 personnel in force package E would yield negligible task performance benefits. Since force package D offers comparable capabilities at a lower training cost, it presumably represents the more economical option.

2. Next, we compare force packages E (500 IS2-trained personnel) and F (300 IS2-trained plus 200 IS3-trained personnel). Here, the sole difference is that 200 personnel within force package F have received additional training, i.e., at the IS3 versus IS2 level. When comparing the figure's two corresponding columns, it is apparent that force package F's enhanced training affords significant reductions in vignette-weighted gap probabilities, for many tasks. Thus, the additional IS3-level training yields substantial benefits in effectiveness terms. However, the relative affordability of such additional training must be judged by competent authorities.

[13] The figure's legend shows six discrete colours and their associated gap probabilities. Cells were shaded using a continuous colour scale, which ramped linearly as a function of gap probability between the legend's end points.

Figure 10: Notional vignette-weighted gap probabilities for force packages A-J, assuming sufficient specialists.

In a similar fashion, we can explore the notional implications of excluding all specialists from force packages A through J. Two principal differences exist between this "no-specialists" case (Figure 11) and the sufficient-specialists one (Figure 10), namely:

1. For all force packages, the vignette-weighted gap probabilities for the no-specialists case equal or exceed their sufficient-specialists analogues. This is as expected, since removing specialists decreases force packages' aggregate training levels, thereby rendering them less effective.

2. Of the ten options compared here, force package J's non-specialist personnel are the most highly trained (Table 7). When force package J includes sufficient quantities of specialist personnel, its vignette-weighted gap probabilities for all tasks are less than 1% (Figure 10). Thus, in the sufficient-specialists case, force package J's task performance in relation to a domestic CBRN event would almost always be adequate. Conversely, when force package J is devoid of specialists, its vignette-weighted gap probabilities for many tasks are much greater (Figure 11).

Both differences discussed above suggest that, with respect to the notional data, specialist personnel are critical enablers of adequate CAF performance in relation to a domestic CBRN event. The results of the Canada COM/CJOC option analysis led to an analogous, uncontroversial conclusion concerning specialists' importance. Yet, the real-world analysis did not merely reiterate a widely held belief within the CAF's CBRN defence community. Rather, it quantitatively illustrated specialists' importance, based on our systematic VITRO approach.

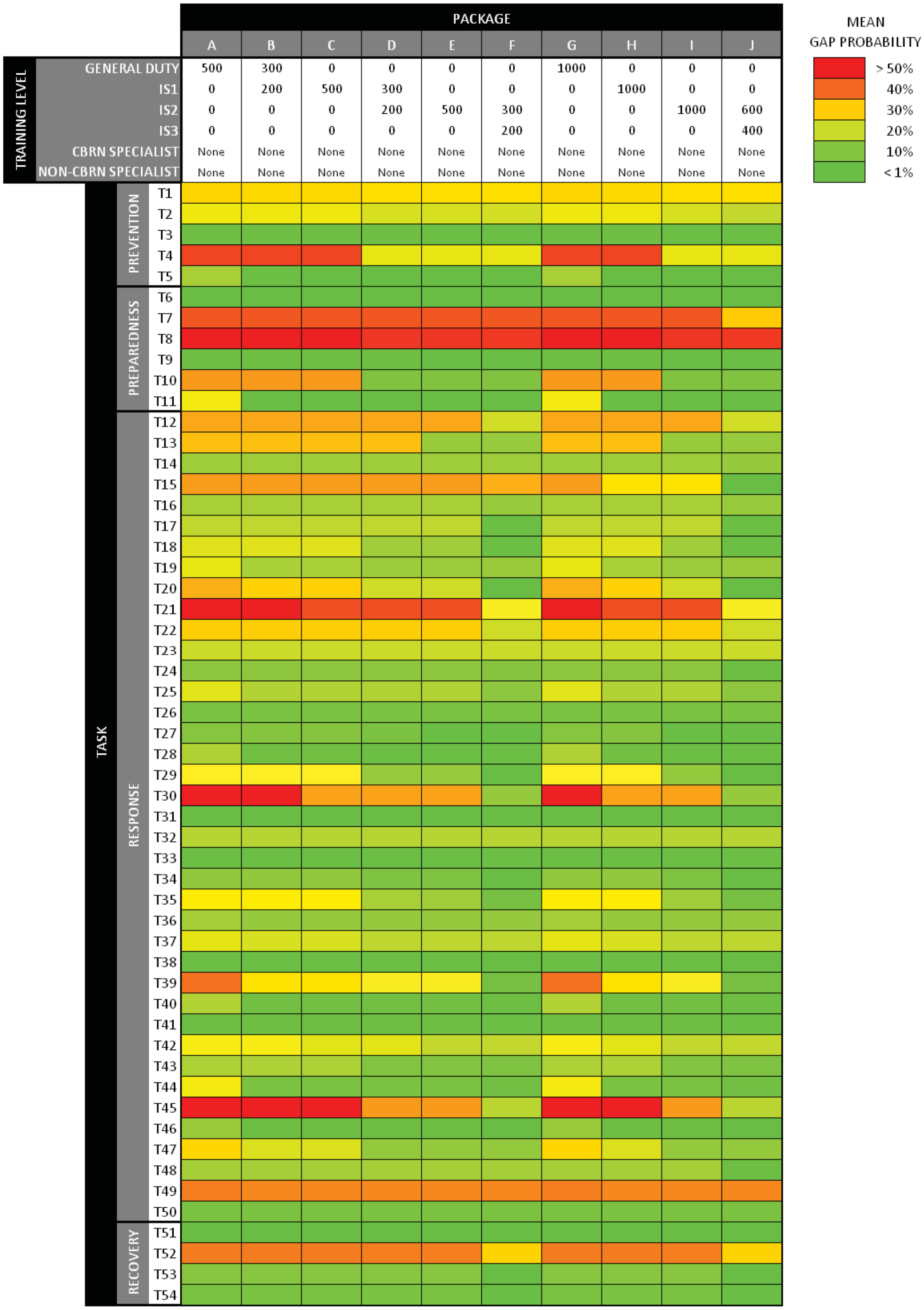

Figure 11: Notional vignette-weighted gap probabilities for force packages A-J, in the absence of specialists of any kind.

5.4 Discussion

Our option analysis method enables comparisons between multiple force packages, in relation to a domestic CBRN event. It does so by (a) aggregating the results of the vignette, task, and requirement analyses in a rigorous manner and (b) providing clear means for visualizing the results. Thus, it reduces the complexity of the planning challenge and yields a quantitative basis for decision making. In particular, representations such as Figure 10 directly inform and facilitate fundamental discussions concerning trade-offs between force packages' resource commitments, training costs, and capabilities. For these reasons, the option analysis method and results were welcomed and applied during the Canada COM/CJOC concept development effort, by all organizational levels.

This final component of the VITRO analyses, like the others, has some limitations. First, the notional option analysis considered only the quantities and training profiles of personnel comprising each force package when determining vignette-weighted gap probabilities. The natures, quantities, and dispositions of equipment at each force package's disposal were not considered. This omission is equivalent to assuming that all necessary equipment was available to each force package, in every situation. Had equipment also been considered during the requirement and option analyses (of Sections 4 and 5, respectively), larger vignette-weighted gap probabilities would have been obtained in Section 5. In that respect, the results contained in this chapter are consequently rather best-case.

Second, since uncertainties were not assessed in the vignette, task, and requirement analyses, the option analysis (which builds upon previous results) also omits uncertainties. Had uncertainty values for the inputs been available for the three previous parts, uncertainties for the option analysis' results could have been determined.

Third, our notional example considered force packages containing either sufficient quantities of specialists (to perform any task, within any vignette) or none at all. Using these two limiting cases, we illustrated how the impact of specialists' presence/absence can be estimated quantitatively during an option analysis. However, thorough requirement and option analyses require detailed considerations of the many specialist types. Fortunately, our methods can be extended readily for such purposes.

Finally, we assumed that an entire force package would be devoted to performing a single task. That assumption is best-case and facilitated our illustration of the option analysis method. Specifically, it meant that each force package's vignette-weighted gap probabilities $G_{f,Tj}$ pertained to single tasks in isolation. However, in relation to a potential real-world domestic CBRN event, the CAF might be requested to perform multiple tasks concurrently or a single task at multiple locations. In either case, only a fraction of the force package's total resources would be assigned to each task/location. To address such situations, it would be relatively straightforward to extend our option analysis method to calculate multiple-task/multiple-location vignette-weighted gap probabilities.

6 Summary and perspectives

In this report, we have described the VITRO analyses approach used to support Canada COM/CJOC's development of a concept for domestic CBRN event response. We have illustrated the approach in an unclassified manner, by using notional data throughout the report.

The method's four sequential analyses each address a fundamental planning question in a systematic and transparent way. Whereas vignette analysis provides likelihood estimates for domestic CBRN events of interest, task analysis yields performance request probabilities for potential CAF tasks. Requirement analysis offers systematic means for assessing what the CAF would require to perform such tasks adequately, in various situations, in terms of personnel quantities and training levels. Finally, option analysis rigorously aggregates the results of the three foregoing analyses, to estimate various force packages' performance with respect to a multitude of potential tasks. Such results' high-level, quantitative nature readily enables a decision maker to weigh potential trade-offs between personnel commitments, training investments, and consequent force package capabilities. Thus, option analysis provides quantitative means for comparing the degrees of domestic CBRN event response capability afforded by various resourcing options.

Many attributes of the VITRO analyses approach contributed to its successful application to Canada COM/CJOC's concept development for domestic CBRN event response. These included:

- *Early articulation of key planning questions.* The early identification of four questions intrinsic to the Canada COM/CJOC planning effort was vital. Such questions enabled us to frame the analytical objectives in simple terms and thereby reduced the planning problem's conceptual complexity.

- *Tailored design of analytical methods.* We designed each of the VITRO analyses to address a specific and fundamental planning question directly. Such focused design yielded multiple benefits. First, it enabled us to clearly state objectives at the outset of each data collection workshop. Such clarity helped to persuade workshop participants to do their best during these intellectually taxing events. Second, by briefing the results of each analysis as they became available, we were able to demonstrate consistent progress to stakeholders at Canada COM/CJOC and to external organizations. Beyond providing justification for each subsequent analytical phase, such briefings increased stakeholder interest in the larger analytical effort. Finally, since each analysis pertained to a specific planning question, the results could be presented to decision makers in a relatively simple, linear narrative form. For decision makers, this facilitated comprehension and engendered confidence regarding the analytical effort.

- *Quantitative nature of inputs and results.* In some communities, likelihood estimates concerning potential events (or the like) are frequently expressed in qualitative terms (e.g., as "low", "moderate", or "high"). Some practitioners argue that their use of qualitative scales is justifiable when estimates are highly uncertain. On the contrary, we believe that the use of qualitative estimates in such situations is wrongheaded. That is, given an uncertain planning environment, we contend that the use of precise language is essential to reduce complexity and make progress efficiently. Imprecise, qualitative terms such as “low” and “moderate” are subjective and therefore ambiguous. Because their meanings differ from person to person (and from situation to situation), couching estimates in such terms can engender misunderstandings and controversy and may thereby complicate an already complex planning environment. Conversely, quantitative likelihood estimates are unambiguous. For example, a likelihood estimate of 20% per annum has a precise, unmistakable meaning, even if a large uncertainty is associated with it. During data collection workshops, the use of quantitative estimates engenders common understanding, which enables participants to spend their time and energy efficiently, discussing the validity of specific likelihoods (rather than trying to resolve misunderstandings stemming from ambiguous, qualitative terms). Similarly, the use of unambiguous, quantitative values facilitates the effective communication of results to decision makers.

- *Systematic aggregation of inputs and results.* Historically, as currently, CBRN defence planning has been complicated greatly by the need to combine many diverse, low-level planning inputs to yield high-level estimates that are well suited for decision making purposes. For example, we aggregated 4557 notional inputs to obtain 54 vignette-weighted gap probabilities for each force package listed in Figure 10 and Figure 11. Presumably, such aggregation would be impossible to do reliably without a systematic, quantitative approach. Even then, aggregation methods must be valid and transparent if the high-level results are to be considered reliable.[14] Our VITRO analyses' methods are quantitative, systematic, and transparent. They not only serve to aggregate inputs, they also readily enable identification of the driving factor(s) behind each high-level result. Though highly useful, such traceability is not a property of every planning effort.

- *Succinct means of visualization.* Many different visualization schemes could be used to communicate the VITRO analyses' results. During the Canada COM/CJOC analysis, we opted for those depicted in this report, because they enable the main results of each analysis to be represented in a single figure (or possibly two). Such means enabled us to communicate results to senior decision makers succinctly, without overly reducing the scope of the information presented.

Though their inputs and results were inherently uncertain, the VITRO analyses and their results were embraced at all organizational levels, during the Canada COM/CJOC concept development effort. They were broadly accepted because they reduced the complexity of a difficult and longstanding planning problem, via rigorous, quantitative, and transparent means, which engendered confidence in planners and decision makers alike. Since the completion of the Canada COM/CJOC analyses, we have received expressions of interest from other organizations within the CAF and the Government of Canada. As described by the following paragraphs, we hold that the VITRO analyses are applicable (whether in isolation or in combination, following minor modifications) to a host of other planning problems.

[14] Here, the use of quantitative estimates has another advantage over qualitative ones. To aggregate qualitative estimates, many practitioners first map their low-level qualitative inputs to low-level quantitative ones. Such mapping schemes can be rather arbitrary, controversial, or even demonstrably flawed.

The modular nature of the VITRO analyses facilitates their application in other planning areas. Because they are modular, they can be applied in isolation to address specific topics. For instance, the vignette analysis method could be used independently, as part of a threat assessment study. Alternatively, one or more VITRO analyses could be used in combination (with each other or with additional methods). For example, the vignette analysis method could be combined with an event consequence assessment method for risk assessment purposes. Finally, aspects of each VITRO analysis method could be extended or modified as necessary. For instance, the vignette analysis method could be adapted to yield absolute vignette probabilities rather than relative ones.[15] Other possible extensions include the use of alternative data elicitation approaches, the incorporation of equipment considerations, the quantification and propagation of uncertainties, and the gauging of force packages' ability to perform concurrent tasks adequately.

We have applied the VITRO approach during real-world planning at Canada COM/CJOC and to notional data in this report. In both cases, the context involved responses to potential domestic CBRN events. Such specificity is not a feature of the VITRO approach (which is generic) but rather of the vignette and task sets that we have used. One can readily apply the approach in other planning contexts, simply by adopting vignette and task sets which are appropriate to the problem at hand. For example, one could repeat the VITRO analyses to inform CAF planning concerning potential CBRN events during military operations abroad. Alternatively, one could use the approach inform planning (by the CAF or other government departments) for humanitarian assistance or disaster response (whether domestic or foreign). Thus, though we have used the VITRO approach initially in a particular CBRN defence-related context, its potential applications are diverse and many.

[15] Mathematically, such an extension would be trivial. To do so, one need only multiply the relative vignette likelihoods by the probability of a domestic CBRN event occurring during a specified timeframe. However, obtaining a demonstrably accurate or uncontroversial event probability per unit time would be non-trivial.

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Annex A Tabular summary of vignette set

Vignettes are typically written in narrative form and may contain large amounts of information. If a set's vignettes are drawn from multiple sources, then their narrative formats may differ. To consolidate and organize key pieces of vignette-specific information, a tabular summary of the Canada COM/CJOC vignette set was created to inform concept development. The summary was of the form depicted in Table A-1 and proved to be a useful reference aid during the workshops devoted to vignette, task, and requirements analysis. The partial vignette-specific data contained in Table A-1 pertain to the notional vignette set.

Table A-1: Table for summarizing vignettes prior to their likelihood estimation.

Agent Class	Vignette Identifier	Vignette Description	Vignette Origin	Fatalities	Persons Injured or Ill	Persons Hospitalized	Persons Contaminated	Persons Evacuated	Self-Evacuated Persons
Chem	C1								
Chem	C2								
Bio	B1								
Bio	B2								
Bio	B3								
Bio	B4								
Rad	R1								
Rad	R2								
Nuc	N1								
Haz	H1								
Haz	H2								
Haz	H3								

During analysis of the vignette set, the columns of Table A-1 would be populated as follows:

1. *Agent class*: the nature of the agent released in each vignette, i.e., chemical, biological, radiological, nuclear, or hazardous material.

2. *Vignette identifier*: a concise label associated with each vignette.

3. *Vignette description*: a brief descriptor containing:

    a. the specific agent released in each vignette,

    b. whether the release was overt or covert,

    c. the means of dissemination used, and

    d. the target involved.

4. *Vignette origin*: a reference to the document from which each vignette originated.

5. *Fatalities*: the number of deaths resulting from each event.

6. *Persons ill or injured*: the number people who are made ill or wounded due to each event.

7. *Persons hospitalized*: the number of people requiring hospitalization due to each event.

8. *Persons contaminated*: the number of people requiring decontamination due to each event.

9. *Persons evacuated*: the number of people requiring evacuation by authorities.

10. *Self-evacuated persons*: the number of people fleeing the affected area via their own means.

Annex B Canada COM/CJOC task set

During the Canada COM/CJOC task analysis, a set of 54 tasks or task types was used (Table B-1). The tasks were divided into pre-event (i.e., "prevention" and "preparedness") and post-event (i.e., "response" and "recovery") temporal phases. Post-event tasks were further subdivided spatially, based on where they would be performed i.e., into either a "hot" zone containing contaminants, an uncontaminated "cold" zone, or an intervening "warm" zone in which decontamination and related tasks are conducted.

Table B-1: Task set used during Canada COM/CJOC concept development

<u>Prevention phase</u>

- Co-operate with intelligence community
- Provide CBRN technical assistance
- Deterrence (e.g., exercises and strategic messaging)
- Plan and execute counter-proliferation operations (e.g., Proliferation Security Initiative)

<u>Preparedness phase</u>

- Conduct planning
- Develop mutually agreed operational procedures with mission partners
- Develop and conduct individual training
- Develop and conduct collective training
- Protect DND critical infrastructure
- Procure equipment

<u>Response phase</u>

All zones

- Assist with citizen evacuation
- Casualty evacuation
- Fatality management
- Engineering support
- Isolation and quarantine

Hot zone

- Support National CBRNE Response Team
- Infrastructure stabilization (e.g., shoring, short-term preparation)
- Mobility support (e.g., clearing rubble)

Hot and warm zones

- Reconnaissance (e.g., detection and identification)
- Helicopter/UAV reconnaissance
- Survey (i.e., delineate contaminated area)

Warm zone

- Decontaminate military personnel
- Decontaminate civilians
- Decontaminate equipment
- Decontaminate vehicles
- Decontaminate buildings and terrain
- Effluent control (black/grey water from CAF decontamination only)
- Environmental health (e.g., effluent/waste management)

Warm and cold zones

- Monitoring
- Cordon
- Collective protection (COLPRO)
- Medical treatment
- Provision of medical countermeasures

Cold zone

- CBRN liaison (other government departments, bilateral, etc.)
- Scientific support
- Movements (e.g., strategic airlift)
- Tactical transport (e.g., helicopters, ground vehicles)
- On-site incident management
- Communications support
- Hazard warning and reporting
- Security element
- Medical evacuation
- Mass care (e.g., sheltering, feeding, and related services)
- Infrastructure protection
- Counter-mobility support (i.e., excluding people from an area)
- Critical resource logistics and distribution
- Traffic control
- Personnel recording and tracking (i.e., technicians and civilians)
- Public affairs

<u>Recovery phase</u>

All zones

- Be prepared to continue beyond anticipated end of CAF mission

Cold zone

- CBRN liaison (other government departments, bilateral, etc.)
- Maintain CAF records
- Turn over tracking to civilian organizations

Annex C Notional Personnel Requirements

In this annex, we present the notional personnel requirements $r_{Tj,\tau}^{(ai)}$ used to illustrate our analytical approach, as a function of vignette *ai*, task *Tj*, and individual training level τ. Since they are depicted in the main body of this report, notional general duty (Figure 6) and CBRN specialist (Figure 7) personnel requirements are not reproduced here.

When creating notional estimates of non-specialist personnel requirements, we arbitrarily restricted quantities to five discrete values for each training level. For general duty (Figure 6), IS1 (Figure C-1), and IS2 (Figure C-2) requirements, quantities of 0, 100, 200, 300, and 400 personnel were permitted. For the more highly trained IS3 cadre, smaller quantities of 0, 25, 50, 75, and 100 personnel were used (Figure C-3). Note that during the Canada COM/CJOC analysis, such discrete levels were not used. Rather, CJOC personnel estimated the number of personnel at required at each training level as precisely as possible, for each task-vignette pair.

When creating notional estimates for CBRN specialist (Figure 7) and non-CBRN specialist (Figure C-1) personnel requirements, we used only two personnel quantities, i.e., zero and greater than zero. Conversely, during the Canada COM/CJOC requirement analysis, the quantity of specialists required was estimated as precisely as possible for each task-vignette pair.

For each task-vignette pair, we independently determined notional personnel requirements for each training level, on a random basis, based on the following arbitrary probability distributions:

1. For general duty personnel, the probabilities of a given task-vignette pair requiring 0, 100, 200, 300, or 400 personnel at each training level were 70%, 15%, 8%, 5%, and 2%, respectively. This probability distribution was also used to determine notional IS1 and IS2 personnel requirements for each task-vignette pair.

2. For IS3 personnel, the probabilities of a given task-vignette pair requiring 0, 25, 50, 75 or 100 personnel at each training level were 70%, 15%, 8%, 5%, and 2%, respectively.

3. For CBRN specialist personnel, the probability of a given task-vignette pair requiring more than one specialist was 20%. For non-CBRN specialist personnel, the probability of requiring more than one specialist was also 20%.

Notional personnel requirements were not estimated for task-vignette pairs having task request probabilities of zero (i.e., $p_{Tj}^{(ai)} = 0$; Figure 4). For such task-vignette pairs, the corresponding cells in the notional requirements matrices (i.e., Figure 6, Figure 7, and Figure C-1 to Figure C-4) are marked as being "not applicable", using grey shading.

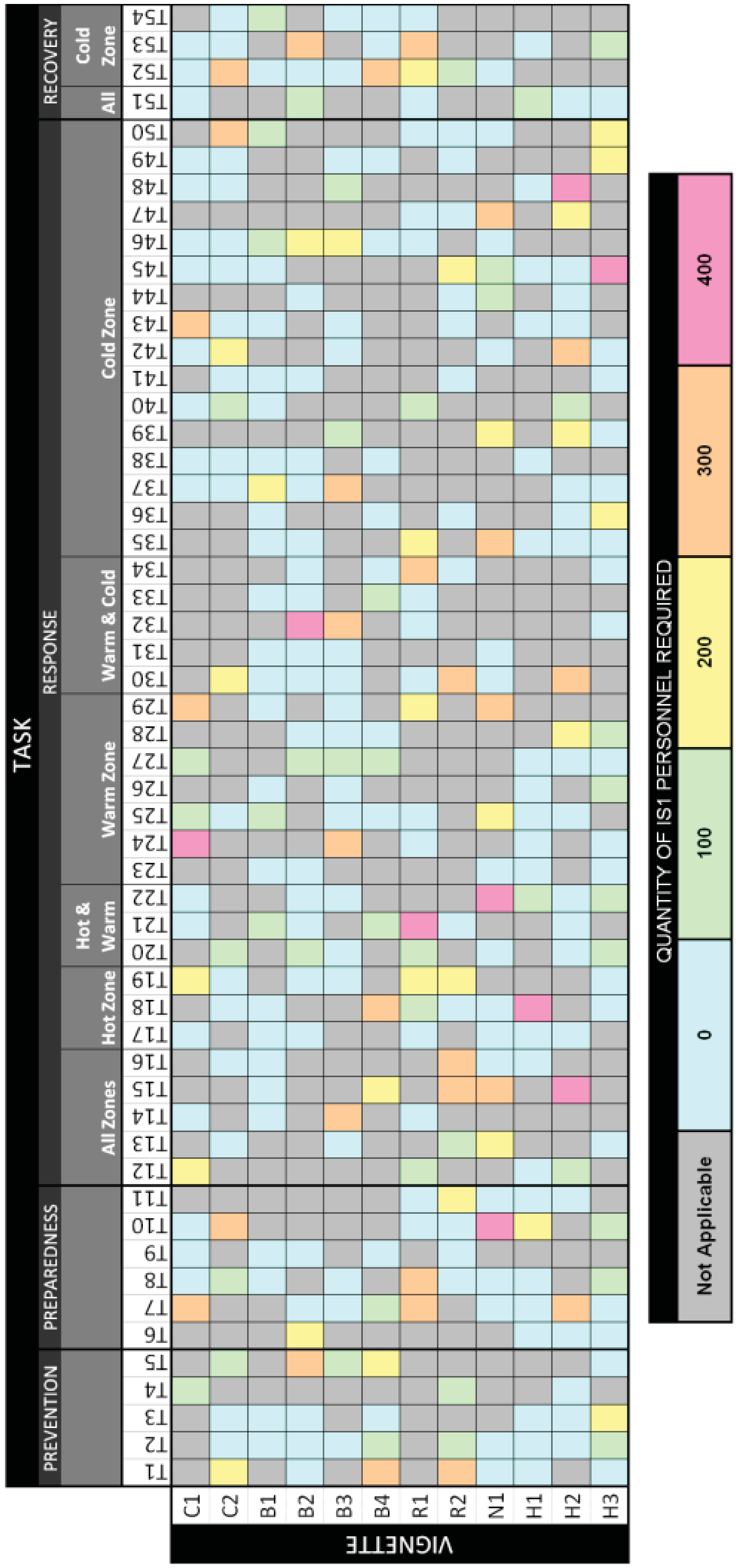

Figure C-1: Notional quantities of IS1-trained personnel required to perform each task adequately within each vignette.

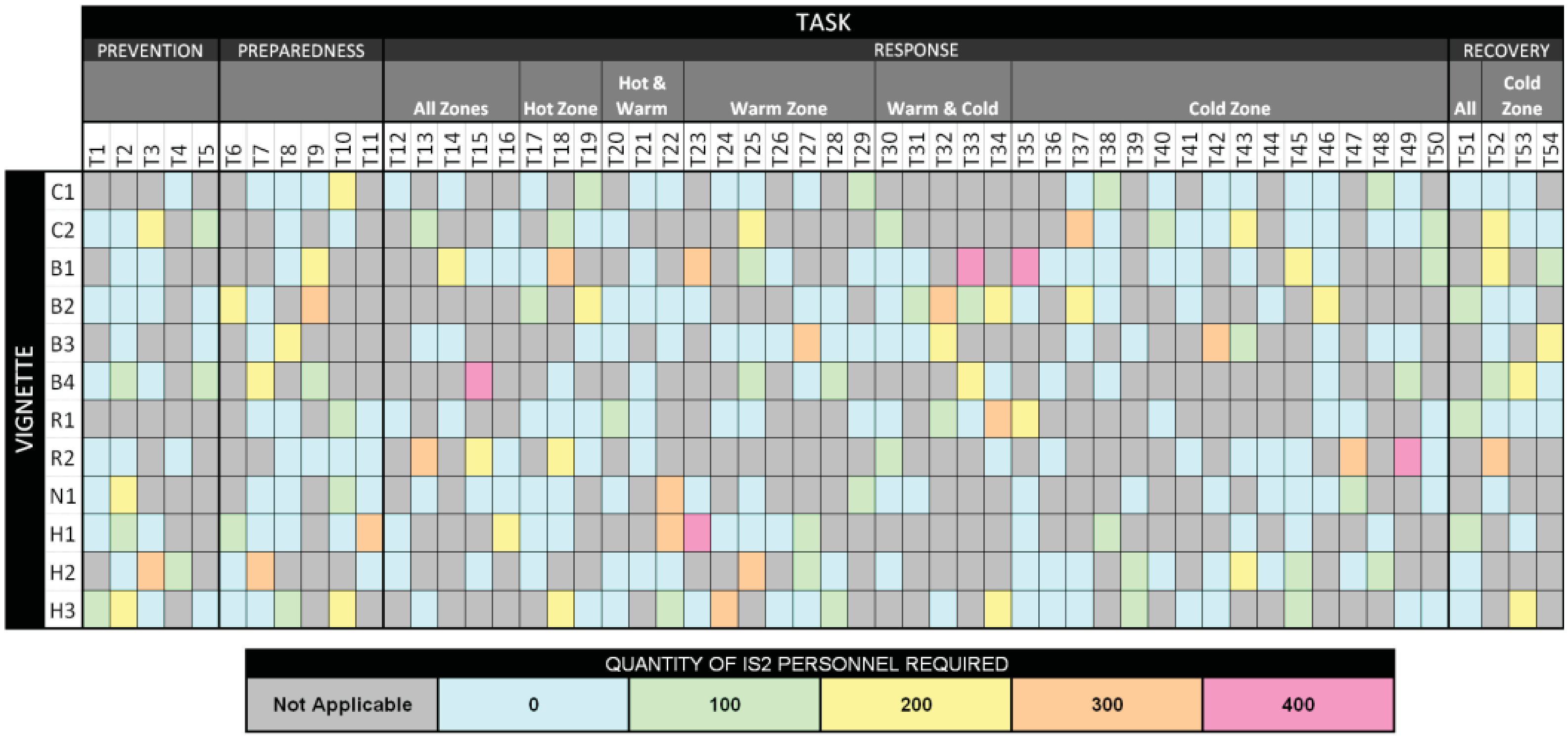

Figure C-2: Notional quantities of IS2-trained personnel required to perform each task adequately within each vignette.

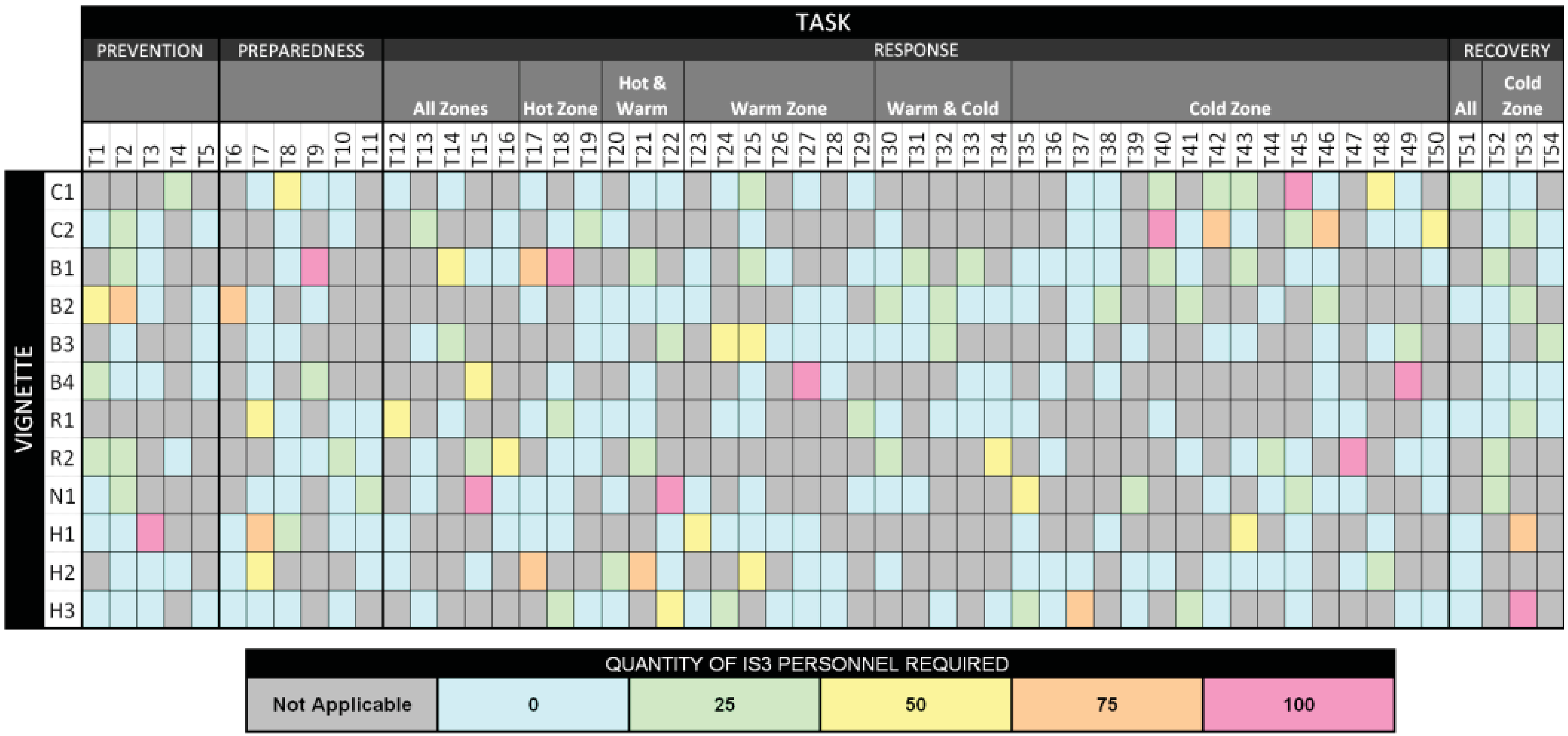

Figure C-3: Notional quantities of IS3-trained personnel required to perform each task adequately within each vignette.

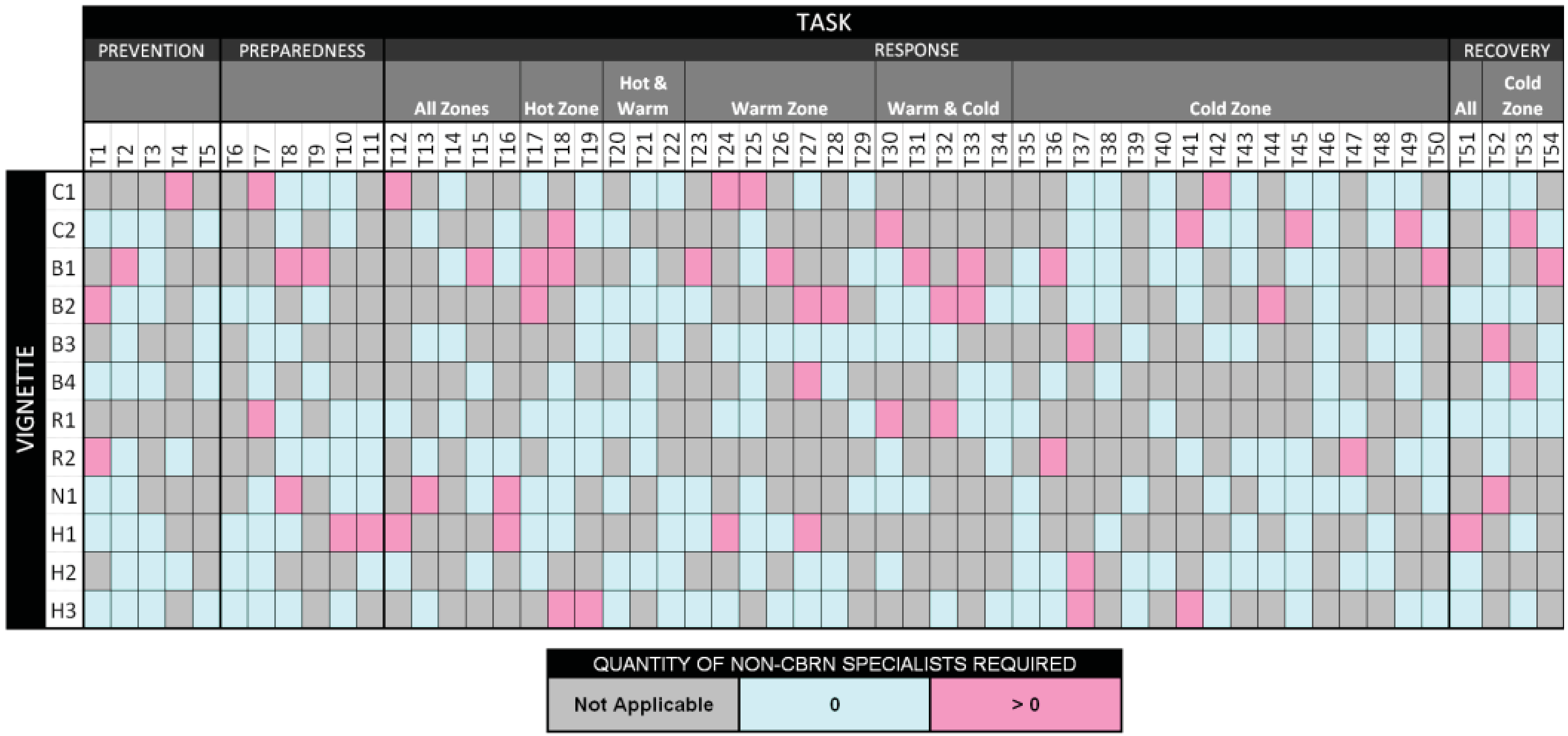

Figure C-4: Notional quantities of non-CBRN specialists required to perform each task adequately within each vignette.

Annex D Notional training level-specific gap probabilities for force package B

In Section 5.2.1's worked example, we demonstrated how training level-specific gap probabilities were determined for force package B, with respect to the performance of task T30 in the context of vignette B2, i.e., $\gamma_{B,T30,\tau}^{(B2)}$. In this annex, we present force package B's training level-specific gap probabilities for all task-vignette pairs. The complete set of force package B's gap probabilities $\gamma_{B,Tj,\tau}^{(ai)}$ is depicted in training level-specific matrices.

For non-specialist training levels, the general duty, IS1, IS2, and IS3 gap probabilities are presented in Figure D-1 to Figure D-4, respectively. Within each such figure, cells are shaded according to the training level-specific gap probability of the corresponding task-vignette pair. Gap probabilities of zero (i.e., an unmet personnel requirement) and unity (i.e., a satisfied personnel requirement) are denoted respectively by red and green cell shading. A grey-shaded grey indicates that the associated task is not applicable within the context of the corresponding vignette. The numerical value within each cell indicates the quantity of force package B's personnel at the given training level who would be allocated to satisfy the personnel requirements of the associated task-vignette pair.

Training-level specific gap probabilities for specialist personnel are presented in Figure D-5 to Figure D-8. Of those, the first two figures correspond to CBRN specialist (Figure D-5) and non-CBRN specialist (Figure D-6) gap probabilities, when sufficient quantities of specialists are assumed to be available. Conversely, the remaining two figures reflect CBRN specialist (Figure D-7) and non-CBRN specialist (Figure D-8) gap probabilities when no specialists are available. In all four figures, gap probabilities are indicated using the cell shading scheme described above for the analogous non-specialist figures (i.e., Figure D-1 to Figure D-4).

TASK	PREVENTION					PREPAREDNESS						RESPONSE							
												All Zones					Hot Zone		
VIGNETTE	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19
C1				100			0	100	0	0		0		0			300		0
C2	200	0	200		100			0		0			0			0		0	0
B1		0	200					0	0					0	100	0	0	0	
B2	0	200	0		0	0	0		100								0		0
B3		0			0		0	0					0	200					100
B4	0	0	0		0		0		0						0			0	
R1							100	0		100	200	0		0			0	0	0
R2	100	0		200				0	100	100	0		0		200	0		0	0
N1	0	300					0	0		0	0		0		0	0	0	0	
H1	0	0	0			100	0	0		0	0	100				0	0	0	
H2		100	0	0		0	100				300	0			200		0		
H3	0	0	100		0	200	0	0		0			0					0	0

TASK	RESPONSE																	
	Hot & Warm			Warm Zone							Warm & Cold					Cold Zone		
VIGNETTE	T20	T21	T22	T23	T24	T25	T26	T27	T28	T29	T30	T31	T32	T33	T34	T35	T36	T37
C1		0	0		0	0		0		200								0
C2	0					0					0							0
B1		0		100		100	0			0	0	0		0		0	0	300
B2	0	0	0	0				100	0		300	100	100	0	0	0		0
B3	0		300		300	0	0	0	0	0	0	0	300					0
B4		0				100		0	0					0	300		0	
R1	0	0			0	0				0	300		0	0	0	100		
R2		0									0				0		0	
N1	0		0	0		100				0	0	0				0		
H1			0	100	0	0	0	100								0		
H2	200	100	100			0		0	100		0					0	0	300
H3	0		0	0	100		0	0	0				0		100	100	0	0

TASK	RESPONSE													RECOVERY			
	Cold Zone													All	Cold Zone		
VIGNETTE	T38	T39	T40	T41	T42	T43	T44	T45	T46	T47	T48	T49	T50	T51	T52	T53	T54
C1	200		200		100	0		0	100		0	200		100	0	100	
C2	200		200	0	100	100		200	0		0	0	0		0	300	0
B1	0		100	200		0		0	200				0		100		0
B2	0			100			0		0					0	0	0	
B3		0			0	0			0		200	0			0		0
B4	0								100			300			0	200	0
R1			100						100	0			0	100	200	0	0
R2				300		0	0	0		0		0	100		0		
N1		0			0		0	0	200	0			0		0		
H1	0					0		0			0			100		200	
H2		0	200		0	0	0	0		0	100			100			
H3		0		0	0			0				0	0	300		100	

GAP PROBABILITY FOR GENERAL DUTY PERSONNEL REQUIREMENT		
Not Applicable	0	1

Figure D-1: Notional gap probabilities with respect to force package B's general duty personnel requirements.

Vignette	PREVENTION					PREPAREDNESS						RESPONSE: All Zones					RESPONSE: Hot Zone	
	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18
C1				100			**0**	0	0	0		200		0			100	
C2	200	0	0		100			100		**0**			0			0		0
B1		0	0					0	0					0	0	0	0	0
B2	0	0	0		**0**	200	0		0								0	
B3		0			100		0	0					0	**0**				
B4	**0**	100	0		200		100		0						200			**0**
R1							**0**	**0**		0	0	100		0			0	100
R2	**0**	100		100				0	0	0	200		100		**0**	**0**		0
N1	0	0					0	0		**0**	0		200		**0**	0	0	0
H1	0	0	0			0	0	0		200	0	0				0	0	**0**
H2		0	0	0		0	**0**				0	100			**0**		0	
H3	0	100	200		0	0	0	100		100			0					0

Vignette	RESPONSE: Hot Zone	RESPONSE: Hot & Warm			RESPONSE: Warm Zone							RESPONSE: Warm & Cold					RESPONSE: Cold Zone	
	T19	T20	T21	T22	T23	T24	T25	T26	T27	T28	T29	T30	T31	T32	T33	T34	T35	T36
C1	200		0	0		**0**	100		100		**0**							
C2	0	100					0					200						
B1			100		0		100	0			0	0	0		0		0	0
B2	0	100	0	0	0				100	0		100	0	**0**	0	0	0	
B3	0	0		0		**100**	0	0	100	0	0	0	0	**0**				
B4			100				0		100	0					100	0		0
R1	200	100	**0**			0	0				200	0		0	0	**0**	200	
R2	200		0									**0**				0		0
N1		0		**0**	0		200				**0**	0	0				**0**	
H1				100	0	0	0	0	0								0	
H2		0	0	0			0		0	200		**0**					0	0
H3	0	100		100	0	0		100	0	100				0		0	0	200

Vignette	RESPONSE: Cold Zone														RECOVERY: All	RECOVERY: Cold Zone		
	T37	T38	T39	T40	T41	T42	T43	T44	T45	T46	T47	T48	T49	T50	T51	T52	T53	T54
C1	0	0		0		0	**0**		0	0		0	0		0	0	0	
C2	0	0		100	0	200	0		0	0		0	0	**0**		**0**	100	0
B1	200	0		0	0		0		0	100				100		0		100
B2	0	0			0			0		200					100	0	**0**	
B3	**0**		100			0	0			200		100	0			0		0
B4		0								0			100			**0**	0	0
R1				100						0	0			0	0	200	**0**	0
R2					100		0	0	200		0		0	0		100		
N1			200			0		100	100	0	**0**			0		0		
H1		0					0		0			0			100		0	
H2	100		200	100		**0**	0	0	0		200	**0**			0			
H3	0		0		0	0			**0**				200	200	0		100	

GAP PROBABILITY FOR IS1-TRAINED PERSONNEL REQUIREMENT

Not Applicable	0	1

Figure D-2: Notional gap probabilities with respect to force package B's IS1-trained personnel requirements.

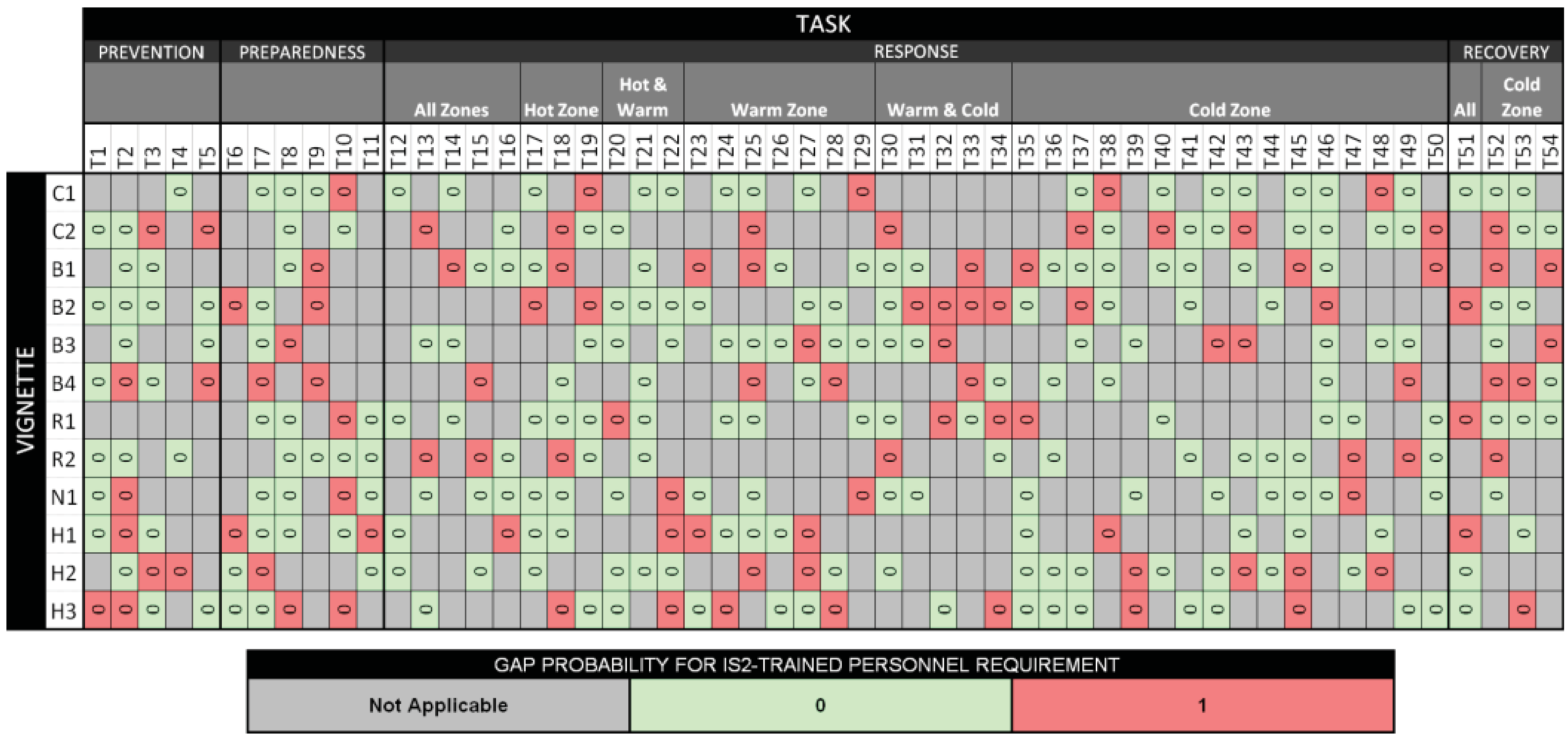

Figure D-3: Notional gap probabilities with respect to force package B's IS2-trained personnel requirements.

VIGNETTE	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11
TASK	PREVENTION					PREPAREDNESS					
C1				0			0	0	0	0	
C2	0	0	0		0			0		0	
B1		0	0					0	0		
B2	0	0	0		0	0	0		0		
B3		0			0		0	0			
B4	0	0	0		0		0		0		
R1							0	0		0	0
R2	0	0		0				0	0	0	0
N1	0	0					0	0		0	0
H1	0	0	0			0	0	0		0	0
H2		0	0	0		0	0				0
H3	0	0	0		0	0	0	0		0	

VIGNETTE	T12	T13	T14	T15	T16	T17	T18	T19	T20	T21	T22	T23	T24	T25
TASK	RESPONSE													
	All Zones					Hot Zone			Hot & Warm			Warm Zone		
C1	0		0			0		0		0	0		0	0
C2		0			0		0	0	0					0
B1			0	0	0	0	0			0		0		0
B2						0		0	0	0	0	0		
B3		0	0					0	0		0		0	0
B4				0			0			0				0
R1	0		0			0	0	0	0	0			0	0
R2		0		0	0		0	0		0				
N1		0		0	0	0	0		0		0	0		0
H1	0				0	0	0				0	0	0	0
H2	0			0		0			0	0	0			0
H3		0					0	0	0		0	0	0	

VIGNETTE	T26	T27	T28	T29	T30	T31	T32	T33	T34	T35	T36	T37	T38	T39
TASK	RESPONSE													
	Warm Zone				Warm & Cold					Cold Zone				
C1		0		0								0	0	
C2					0							0	0	
B1	0			0	0	0		0		0	0	0	0	
B2		0	0		0	0	0	0	0	0		0	0	
B3	0	0	0	0	0	0	0					0		0
B4		0	0					0	0		0		0	
R1				0	0		0	0	0	0				
R2					0				0		0			
N1				0	0	0				0				0
H1	0	0								0			0	
H2		0	0		0					0	0	0		0
H3	0	0	0				0		0	0	0	0		0

VIGNETTE	T40	T41	T42	T43	T44	T45	T46	T47	T48	T49	T50	T51	T52	T53	T54
TASK	RESPONSE											RECOVERY			
	Cold Zone											All	Cold Zone		
C1	0		0	0		0	0		0	0		0	0	0	
C2	0	0	0	0		0	0		0	0	0		0	0	0
B1	0	0		0		0	0				0		0		0
B2		0			0		0					0	0	0	
B3			0	0			0		0	0			0		0
B4							0			0			0	0	0
R1	0						0	0			0	0	0	0	0
R2		0		0	0	0		0		0	0		0		
N1			0		0	0	0	0			0		0		
H1				0		0			0			0		0	
H2	0		0	0	0	0		0	0			0			
H3		0	0			0				0	0	0		0	

GAP PROBABILITY FOR IS3-TRAINED PERSONNEL REQUIREMENT		
Not Applicable	0	1

Figure D-4: Notional gap probabilities with respect to force package B's IS3-trained personnel requirements.

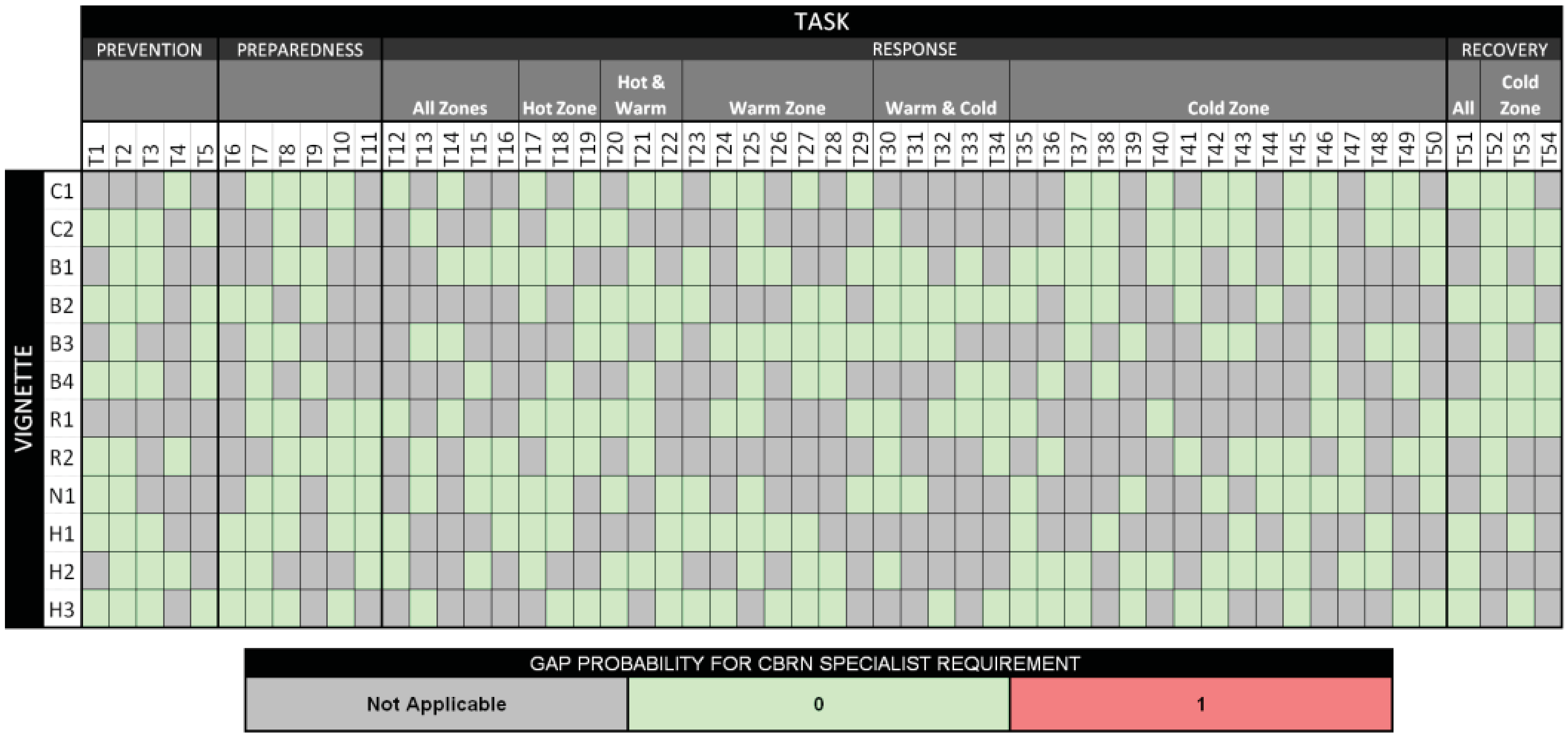

Figure D-5: Notional gap probabilities with respect to force package B's CBRN specialist requirements, assuming that sufficient specialists are available.

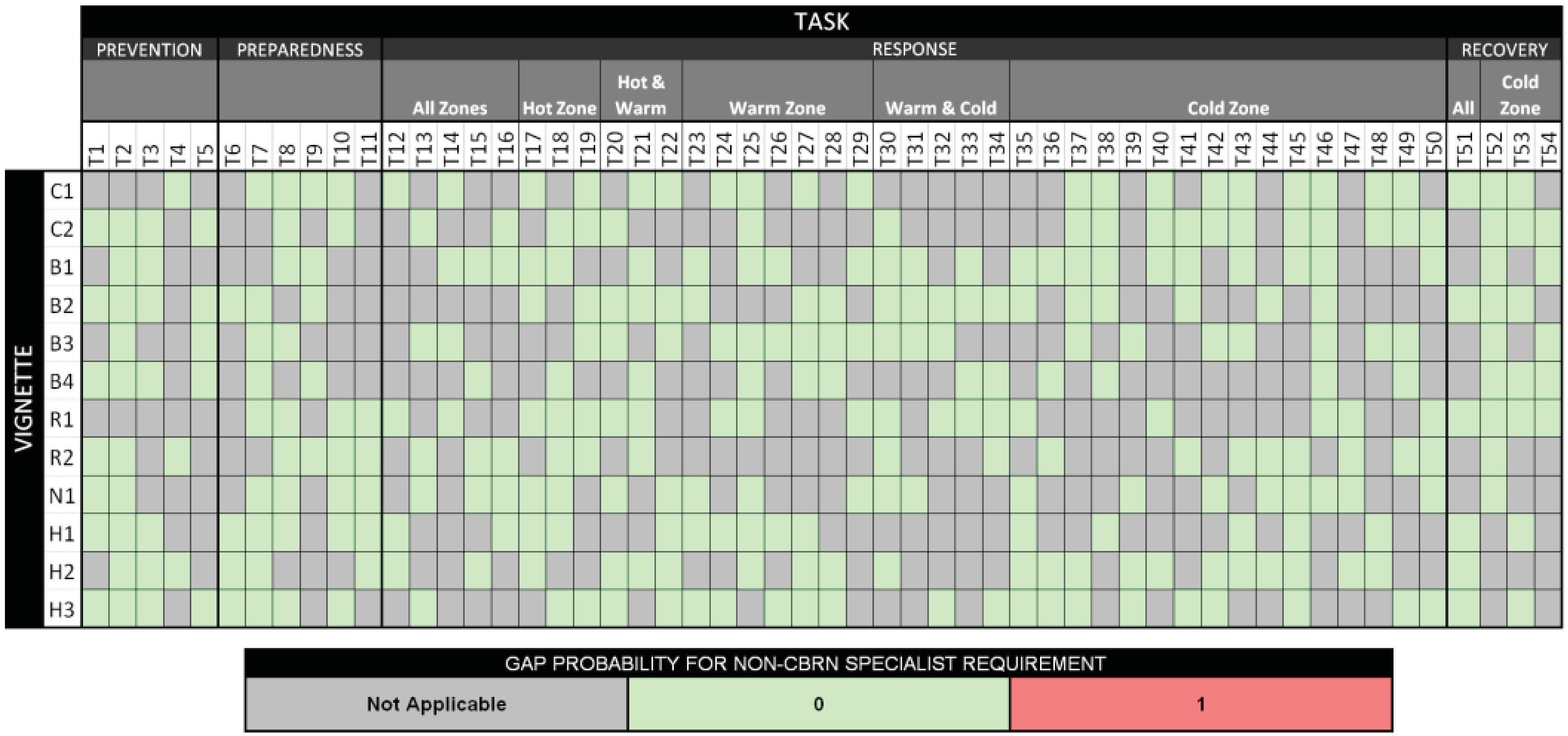

Figure D-6: Notional gap probabilities with respect to force package B's non-CBRN specialist requirements, assuming that sufficient specialists are available.

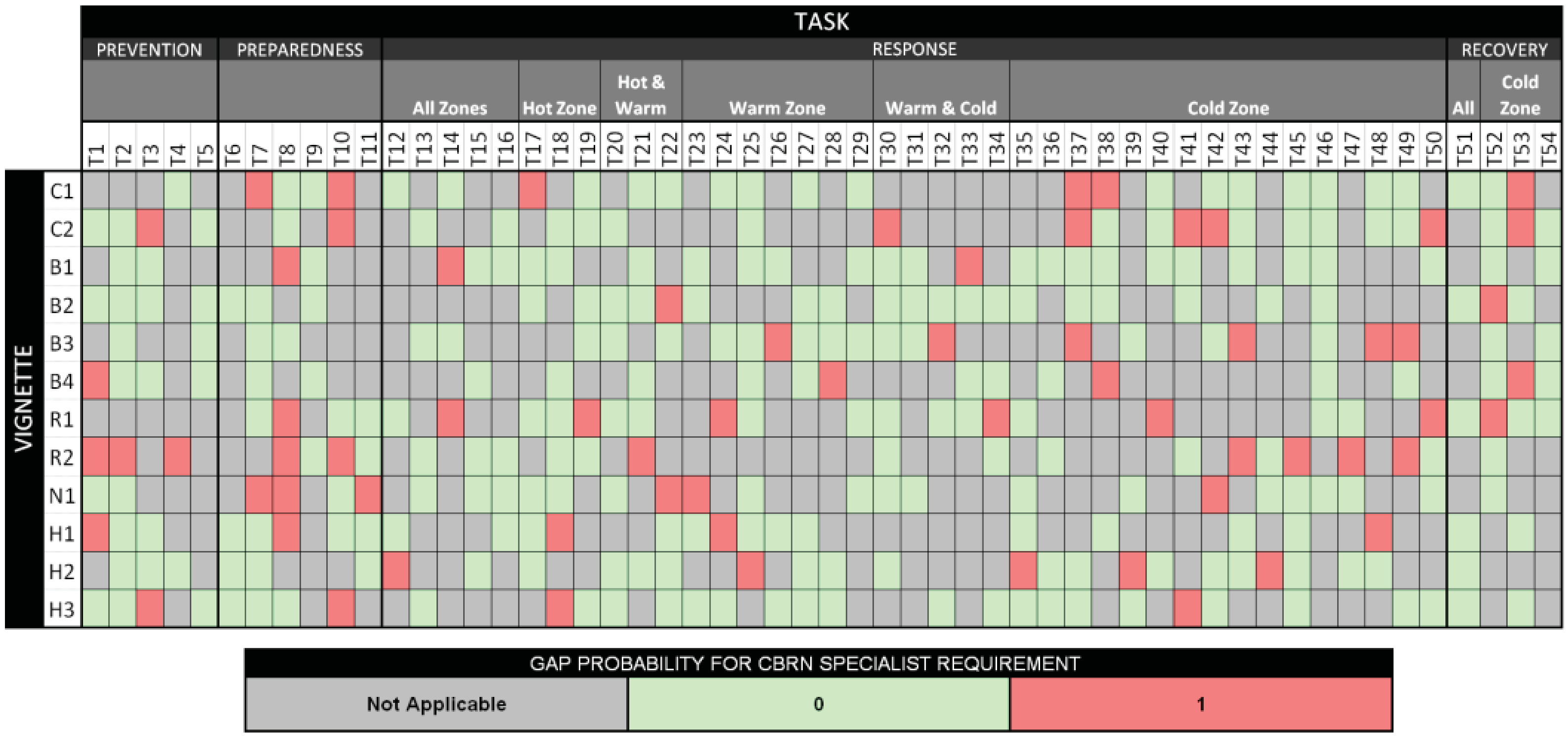

Figure D-7: Notional gap probabilities with respect to force package B's CBRN specialist requirements, assuming that no specialists are available.

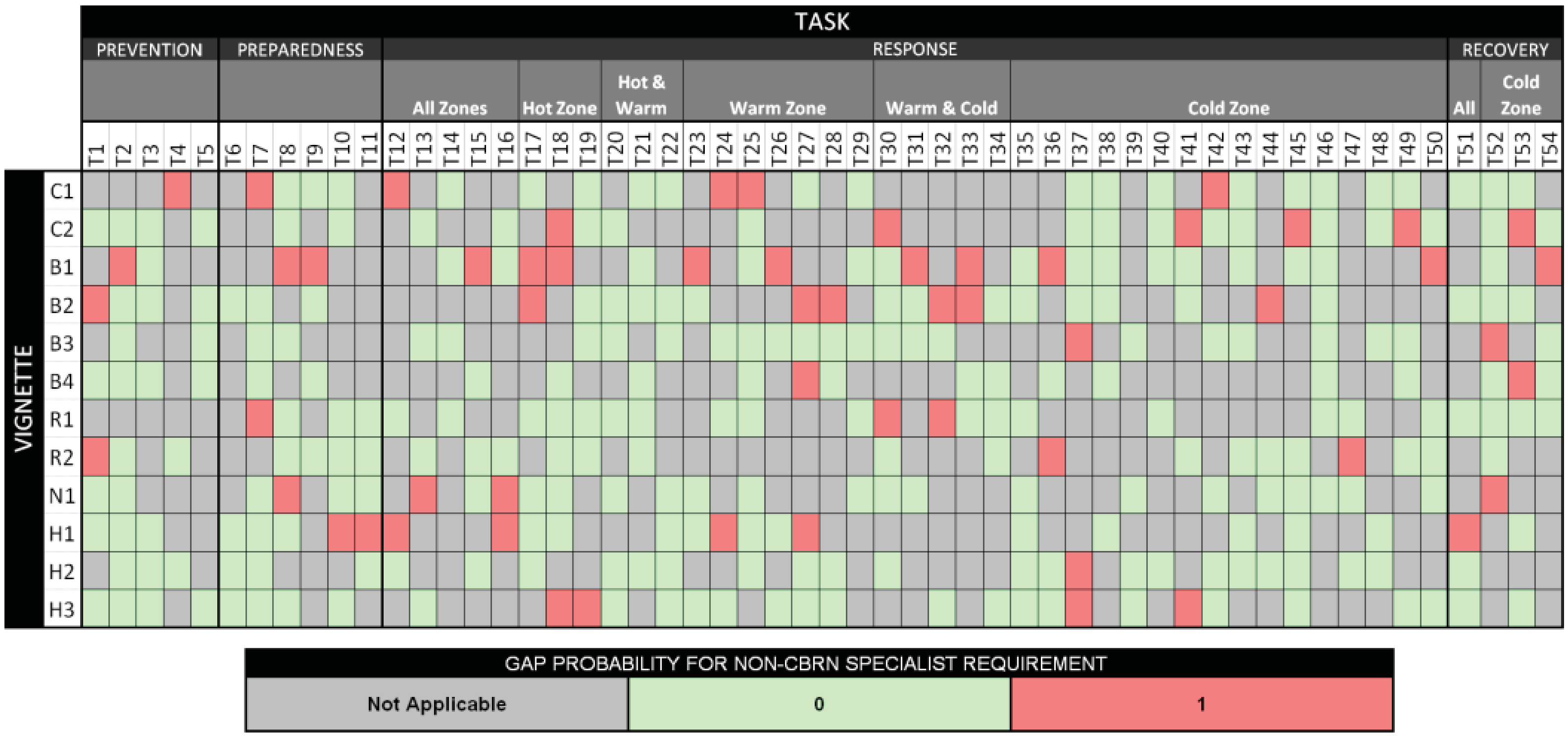

Figure D-8: Notional gap probabilities with respect to force package B's non-CBRN specialist requirements, assuming that no specialists are available.

Annex E Thermometer charts

For a particular force package, a "thermometer chart" directly compares two types of vignette-weighted probabilities. Given a domestic CBRN event, the chart contrasts (a) the likelihoods that various tasks performance would be requested with (b) the likelihoods that the force package could not adequately perform such tasks.

As an example, we present such a chart in Figure E-1, which depicts notional data used previously in this report. Two data series are represented in the figure. The first series (which is plotted using transparent bars) consists of the vignette-weighted task performance request probabilities P_{Tj} that were originally presented in Figure 5. As before, such probabilities are grouped temporally by event continuum phase and sorted within each phase by probability, from highest to lowest. The second series (represented by shaded bars) is composed of force package B's vignette-weighted gap probabilities $G_{B,Tj}$, assuming that sufficient specialists are available.

The notional thermometer chart in Figure E-1 is relatively easy to interpret. The transparent bars represent the likelihoods of the CAF receiving requests to perform specific tasks, given a domestic CBRN event. The shaded bars indicate the likelihoods that force package B would be unable to perform the various tasks adequately, given a domestic CBRN event. Put simply, a thermometer chart contrasts what the CAF might be requested to do in relation to a domestic CBRN event with a force package's ability to perform such tasks adequately. For instance:

a. The figure's transparent bars imply that the performance of task T10 would be requested in relation to ~35% of domestic CBRN events. However, force package B's vignette-weighted gap probability (shaded bars) for task T10 is also ~35%. Thus, though the performance of task T10 would be requested concerning 1 in 3 events, force package B would be unable to satisfy any such requests adequately. Whether such a complete inability to adequately fulfill relatively common task performance requests is acceptable or not would require consideration.

b. More often than not (i.e., for ~52% of events) the performance of task T11 would be requested. Yet, force package B would rarely fail to perform task T11 adequately (i.e., for ~2% of events). As one might wish, this suggests that force package B is well prepared to perform a commonly requested task. However, whether its ~2% vignette-weighted gap probability is sufficiently small may depend on whether the successful performance of T11 is crucial or not.

c. The likelihoods of tasks T49 and T50 being requested in relation to a domestic CBRN event are comparable (i.e., ~38% vs. ~40%). Yet, force package B's vignette-weighted gap probability for task T49 (~37%) greatly exceeds that for task T50 (~1%). Thus, though the tasks' vignette-weighted performance request probabilities are similar, force package B's abilities to perform them adequately differ greatly.

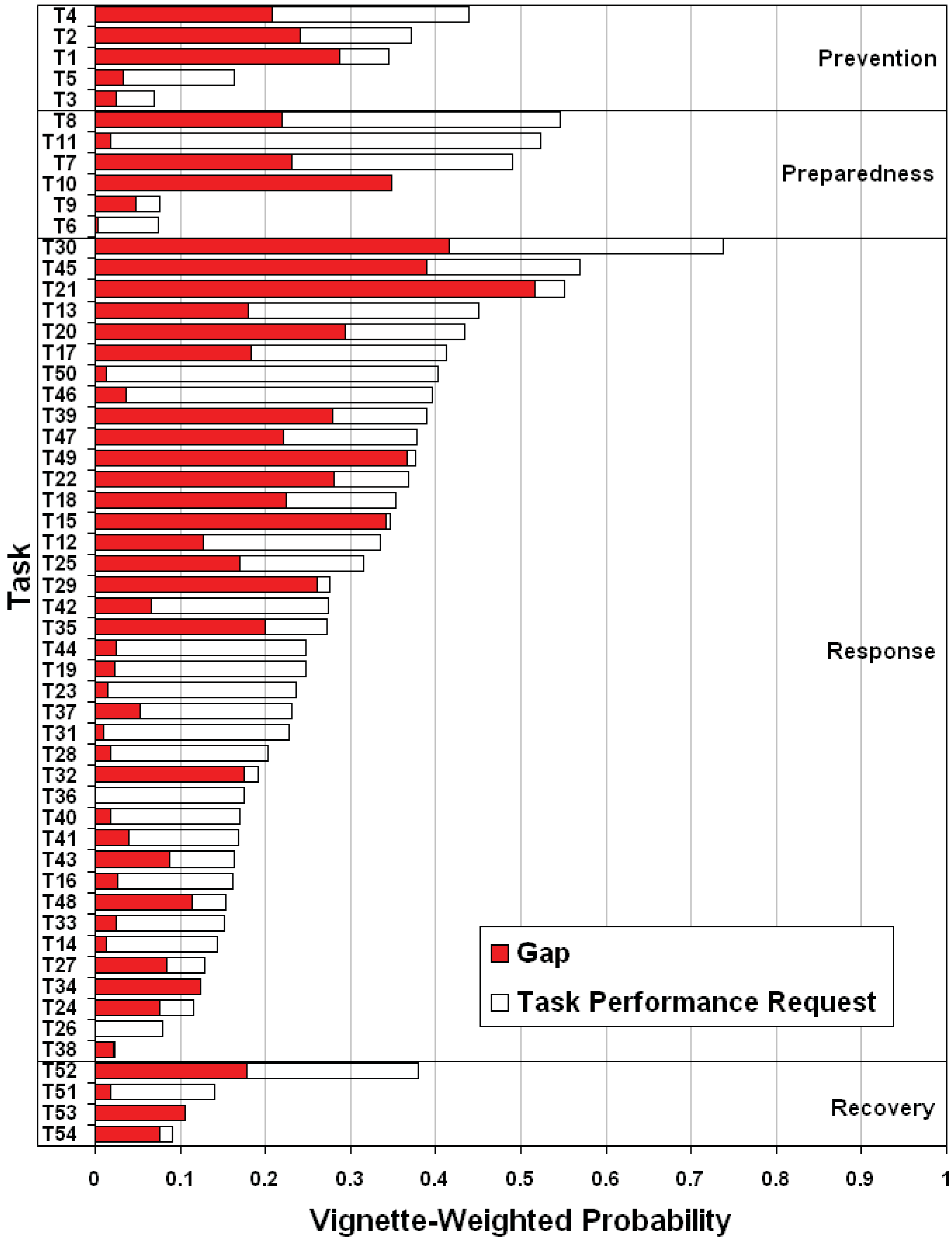

Figure E-1: Notional vignette-weighted task performance request probabilities and vignette-weighted gap probabilities for force package B, assuming sufficient specialists.

List of symbols/abbreviations/acronyms/initialisms

AHP	Analytic Hierarchy Process
CAF	Canadian Armed Forces
Canada COM	Canada Command
CBR MOU	Chemical, Biological, and Radiological Memorandum of Understanding
CBRN	Chemical, Biological, Radiological, and Nuclear
CJOC	Canadian Joint Operations Command
COA	Course of Action
CONPLAN	Contingency Plan
DND	Department of National Defence
DRDC	Defence Research & Development Canada
DRDKIM	Director Research and Development Knowledge and Information Management
FD	Force Development
HAZMAT	Hazardous Material
OAWG	Operational Analysis Working Group
OR&A	Operational Research & Analysis
R&D	Research & Development
US DHS	United States' Department of Homeland Security
VITRO	Vignette, Task, Requirement, & Option

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Using notional data, we describe a systematic, transparent, and generic planning approach that is based on sequential Vignette, Task, Requirement, and Option (VITRO) analyses. Whereas vignette analysis yields likelihood estimates for potential events of interest, task analysis gauges probabilities for tasks that the Canadian Armed Forces (CAF) may be requested to perform in response to such events. Next, requirement analysis produces estimates of what the CAF would need to perform such tasks adequately, across the vignette set. Finally, option analysis aggregates the three foregoing analyses' results, to assess potential force packages' performance versus a range of prospective tasks. The high-level, quantitative results readily enable decision makers to weigh possible trade-offs between resourcing options and consequent force package capabilities. The VITRO approach has been applied to support the development of a CAF concept for domestic Chemical, Biological, Radiological, or Nuclear (CBRN) event response. Though the approach is generic, we have also used a domestic CBRN event response context to frame this report's notional examples.

À l'aide de données fictives, nous décrivons une méthode de planification systématique, transparente et générique fondée sur une succession d'analyses (situations, tâches, besoins, et options - VITRO). Alors que l'analyse de situations estime les probabilités que certains événements surviennent, l'analyse de tâches estime leurs probabilités d'exécution par les Forces armées canadiennes (FAC) si les événements considérés se produisaient. Ensuite, l'analyse des besoins estime ce qu'il faudrait aux FAC pour exécuter ces tâches adéquatement, pour l'ensemble des situations. Enfin, l'analyse d'options regroupe les résultats des trois analyses précédentes, pour évaluer le rendement des ensembles de forces possibles par rapport à une gamme de tâches prospectives. Les résultats quantitatifs de haut niveau permettent facilement aux preneurs de décision de juger des compromis possibles entre les options en matière de ressources et les capacités des ensembles de forces qui en découlent. On a appliqué la méthode VITRO pour appuyer le développement d'un concept des FAC concernant l'intervention à la suite d'un événement chimique, biologique, radiologique ou nucléaire (CBRN) sur le territoire national. Bien qu'il s'agisse d'une méthode générique, nous nous sommes également servis du contexte de l'intervention à la suite d'un événement CBRN pour situer les exemples fictifs du présent rapport.

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concept, development, concept development, plan, plans, planning, vignette analysis, requirement analysis, requirements analysis, option analysis, options analysis, gap analysis, capability analysis, capability gap, capability gaps, analysis, analyses, VITRO, VITRO analyses, VITRO analyses approach, operation, operations, operational research, operations research, operational analysis, CBRN, CBRN defence, CBRN defense, chemical, biological, radiological, nuclear, defence, defense, TIM, toxic industrial materials, hazardous materials, HAZMAT, force structure, domestic operations, Canada Command, Canada COM, Canadian Joint Operations Command, CJOC, Canadian Armed Forces, CAF