Determining Extreme Capability Requirements Using Orthogonal Arrays: An Empirical Study

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Abstract

The basis of defence planning has in the past few years shifted from large single conventional wars to that of preparation for concurrent operations in multiple theatres. Planners often assume that future operations would have staggered starts. This assumption makes the sequence in which the operations are executed consequential with respect to the levels of capabilities needed to meet requirements. Often times, the most demanding sequence is determined by conducting a complete enumeration of all possible sequencing of the planning scenarios. The most stringent capability requirement so determined is then used for planning. This report provides results of a simulation study that shows that it is possible to get a requirement specification that is adequate for over 92% of all future possibilities using considerably fewer sequences based on orthogonal arrays (56 instead of 40320 sequences in the case of eight planning scenarios). It also shows that contrary to popular perception, staggering the starts of the operations does not necessarily lead to reduced requirements.

Résumé

Au cours des dernières années, la planification de la défense s'est transformée : il ne s'agit plus de préparer une grande guerre conventionnelle, mais plutôt des opérations simultanées dans des théâtres multiples. Les planificateurs prennent souvent pour acquis que les futures opérations seront échelonnées dans le temps. Par conséquent, la séquence d'exécution des opérations influence énormément les niveaux de capacités requis pour répondre aux besoins opérationnels. Bien souvent, pour déterminer quelle est la séquence la plus exigeante, on examine toutes les séquences possibles d'exécution des scénarios de planification. Le niveau de capacité correspondant à la séquence la plus exigeante est ensuite utilisé pour la planification. Le rapport ci joint présente les résultats d'une étude par simulation qui montre qu'il est possible d'obtenir une spécification des besoins qui est adéquate pour 92 p. 100 de toutes les opérations futures en utilisant un nombre beaucoup moins élevé de séquences (56 séquences au lieu de 40 320 pour huit scénarios de planification), grâce à la méthode des séries orthogonales. L'étude montre également que contrairement à ce que l'on croit généralement, l'échelonnement des opérations ne réduit pas nécessairement les besoins.

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Executive summary

Determining Extreme Capability Requirements Using Orthogonal Arrays: An Empirical Study

Yaw Asiedu; DRDC CORA TM 2009-053; Defence R&D Canada – CORA; November 2009.

Introduction: The basis of defence planning has shifted from "threat-based" models that dominated thinking in the cold war era, to "capabilities-based" models; often referred to as Capability Based Planning (CBP). A portfolio of Planning Scenarios (PS) is often employed in CBP to describe a representative spectrum of operations in which military forces may be called upon to act.

Militaries are often expected to have the capacity to conduct multiple operations (expressed as PSs) concurrently. It is commonly perceived that the greatest demands would be placed on the military if all the operations were to start on the same day rather than on different days. Given that this is highly unlikely, maintaining the ability to provide large amounts of a capability for this worst case scenario may not be tenable. Consequently, operations are assumed to be staggered and the demand imposed by the most demanding starting order used for planning. If the military can meet this requirement, then it can be assured of having enough capability to meet the requirement in every other circumstance.

The order in which staggered operations are executed has a great influence on the level of capability needed to meet all requirements. Unfortunately, there does not exist a simple approach to determine this figure and often times, the sequence that gives rise to the highest demand G, is determined by conducting a complete enumeration of all possible sequences S. That is, to conduct a factorial experiment. Unfortunately, this can sometimes be time consuming and/or expensive. It may therefore be more reasonable to use only a fraction of all the possible sequences to determine a demand G_o, to use for planning. This study assesses the propriety of using orthogonal arrays (OAs) to identify the subset of sequences to use and to verify that staggering the starts of the PSs leads to reduced capability requirements.

Methodology: The economy of run size afforded by an OA may come at a cost. It is not guaranteed to give a value equal to what a complete factorial design would have produced. Two metrics, *Rank Dominance* and *Relative Deviation* were therefore proposed to measure the propriety of using G_o instead of G for planning. The *Rank Dominance* gives a measure of the risk of not having the capacity to meet future operational requirements if planning is based on G_o and the *Relative Deviation* measures how close G_o is to G.

A Monte Carlo simulation was employed to randomly generate the capability requirements for a number of PSs. At each iteration, requirements were generated for a case of eight PSs. Employing a set of recursive equations, the values of G and G_o were calculated and compared. These calculations were done for requirements of different order of magnitude and PS start separations of 0 (same-day starts), 1, 2 and 3 months.

Principal Results: Based on the results of the simulation study, it can be concluded that in general, G_o is a good approximation for G. More specifically,

1. the required capability was underestimated by only 17.1% in the worst case and only in 13 out of 24,000 cases was the underestimation (i.e., *Relative Deviation*) greater than 15%; and
2. as measured by the *Rank Dominance*, the capability requirements exceeded the requirements for at least 91.8% of all possible sequencing of a given set of PSs in the worst case or in other words, the highest risk of not being able to meet a future demand was 8.2%.

The simulation study also showed that the perception that the most demanding requirements arise when all the operations start on the same day is not always borne out. However, the total requirement for same-day starts is more likely to be greater when the PS separation is longer.

Further Application: This study only looked at the sequencing of a given set of PSs. However, the PS portfolios used for defence planning often consist of a large number of PSs that are categorised into groups. These are combined to generate all possible combinations of PSs based on the level of ambition outlined by military and political leaders. In some instances, the number of legal combinations can be in the tens of thousands. It will therefore be incomprehensible to evaluate all sequences for all combinations. The approach discussed can be extended to address the broader question of determining the particular combination of PSs, amongst all the possible combinations, that gives the sequence with the greatest capability requirement.

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Determining Extreme Capability Requirements Using Orthogonal Arrays: An Empirical Study

Yaw Asiedu ; DRDC CORA TM 2009-053 ; R & D pour la défense Canada – CARO ; novembre 2009.

Introduction : La planification de la défense n'est plus fondée sur la menace, comme dans les modèles qui dominaient la pensée stratégique à l'époque de la guerre froide, mais sur les capacités. On parle désormais de " planification fondée sur les capacités " (PFC). La PFC a souvent recours à une série de scénarios de planification (SP) pour décrire l'éventail des opérations auxquelles les forces armées pourraient être appelées à participer.

Les forces armées doivent souvent avoir la capacité de mener simultanément de multiples opérations (exprimées sous forme de SP). On croit généralement que les forces armées feraient face à une demande plus forte si toutes les opérations commençaient le même jour. Mais cette situation est très improbable, et maintenir les énormes capacités requises pour faire face à ce scénario catastrophe pourrait s'avérer intenable. Par conséquent, on prend pour acquis que les opérations seront échelonnées dans le temps, et la demande résultant de la séquence d'exécution la plus exigeante est utilisée pour la planification. Lorsque les forces armées peuvent faire face à cette demande, elles ont l'assurance d'avoir suffisamment de capacités pour répondre aux besoins opérationnels en toutes circonstances.

L'ordre dans lequel les opérations échelonnées sont exécutées a une énorme influence sur le niveau de capacité requis pour répondre à tous les besoins. Malheureusement, il n'existe pas de méthode simple pour déterminer cet ordre, et bien souvent, la séquence qui correspond à la plus haute demande G est établie en faisant l'énumération de toutes les séquences S possibles, c'est à dire en exécutant un plan d'expérience factoriel. Malheureusement, cela peut demander beaucoup de temps et (ou) d'argent. Par conséquent, il est peut être plus raisonnable d'utiliser seulement une fraction de toutes les séquences possibles pour établir une demande G_o qui sera utilisée pour la planification. L'étude examine s'il convient d'utiliser des séries orthogonales (SO) pour déterminer le sous ensemble de séquences qui seront retenues, et pour vérifier que l'échelonnement des SP mènera à une réduction des capacités requises.

Méthodologie : L'économie d'opérations que permet une SO a parfois un coût. Elle ne garantit pas un résultat égal à ce qu'aurait produit un plan factoriel. Deux paramètres de mesure, soit le coefficient de dominance et l'écart relatif, ont donc été

proposés pour mesurer s'il convient d'utiliser G_o plutôt que G pour la planification. Le coefficient de dominance mesure le risque de ne pas avoir la capacité requise pour répondre aux besoins opérationnels futurs si la planification est fondée sur G_o, et l'écart relatif mesure jusqu'à quel point G_o est proche de G.

La méthode de simulation Monte Carlo a été utilisée pour produire de façon aléatoire la capacité requise pour un certain nombre de SP. À chaque itération, la capacité requise a été établie pour huit SP. À l'aide d'une série d'équations récursives, les valeurs de G et de G_o ont été calculées et comparées. Ces calculs ont été effectués pour des besoins de divers ordres de grandeur et des SP séparés de 0 (commençant le même jour), 1, 2 et 3 mois.

Principaux Résultats : En se fondant sur les résultats de l'étude par simulation, on peut conclure que d'une façon générale, G_o est une bonne approximation de G. En particulier :

1. La capacité requise a été sous estimée par seulement 17,1 p. 100 dans le pire des cas, et cette sous estimation (écart relatif) a été supérieure à 15 p. 100 dans seulement 13 des 24 000 cas.
2. Comme l'a mesuré le coefficient de dominance, la capacité requise a dépassé les besoins pour au moins 91,8 p. 100 des séquences possibles d'une série donnée de SP, dans le pire des cas. Autrement dit, le risque de ne pas être en mesure de faire face à la demande est de 8,2 p, 100 au maximum.

L'étude montre également que contrairement à ce que l'on croit généralement, la demande la plus forte ne correspond pas toujours à la situation où les opérations commencent toutes le même jour. Cependant, la demande totale a de bonnes chances d'être plus élevée lorsque la séparation entre les SP est plus longue.

Autres Applications : L'étude n'a examiné que la séquence d'exécution d'une série donnée de SP. Cependant, les séries de SP utilisées pour la planification de la défense comportent souvent un grand nombre de SP qui sont répartis par groupes. Ces séries sont combinées de façon à produire toutes les combinaisons possibles de SP, en fonction du niveau d'ambition affiché par les chefs militaires et les leaders politiques. Dans certains cas, le nombre de combinaisons légales atteint les dizaines de milliers. Par conséquent, il est impossible d'évaluer toutes les séquences pour toutes les combinaisons. L'approche proposée peut être étendue à la question plus générale qui consiste à déterminer la combinaison particulière de SP, parmi toutes les combinaisons possibles, qui donne la séquence la plus exigeante en termes de capacité.

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1 Introduction

The basis of defence planning has shifted from "threat-based" models that dominated thinking in the cold war era, to "capabilities-based" models; often referred to as Capability Based Planning (CBP). The primary reason for this change was to address an uncertain future environment in which a country's next opponent could not be easily predicted [1]. Furthermore, there was the realization that planning for large single conventional wars often left militaries ill-equipped to respond to smaller concurrent operations that may include operations other than war. With this paradigm shift, the emphasis was placed on delivering capabilities to address a wide range of threats to a nation's security rather than on delivering the capability to defeat a specific adversary [1].

Planning Scenarios (PS) are often employed in CBP to describe a representative spectrum of operations in which military forces may be called upon to act. They provide the context for assessing tasks which must be done, and the degree to which military forces, expressed as capability requirements, might reasonably anticipate being required to undertake each task [2].

While the requirements of single scenarios can often be easily met, multiple scenarios frequently provide significant challenges [3]. It is commonly perceived that the greatest demands would be placed on the military if all the operations were to start on the same day. [1] This is due to the fact that historically, most of the forces have been required in the early stages of operations and that when the starts of the operations are staggered, forces used in an earlier PS can be deployed to a different PS that starts later, during subsequent deployments of the force. Furthermore, given that it is highly unlikely that all operations would start on the same day, maintaining the ability to provide large amounts of a capability for this worst case scenario may not be tenable. Consequently, planning for the future is done under the assumption that the starts of the PSs are staggered.

When the starts of concurrent operations are staggered, the order in which they are executed becomes consequential with respect to the level of capabilities needed to meet the requirements. Unfortunately, there does not exist a simple approach to determine this figure and often times, the most demanding sequence is determined by conducting a complete enumeration of all possible sequences. The most stringent capability requirement so determined is then used for planning. If the military can meet this requirement, then it can be assured of having enough capability to meet the requirements in all other circumstances. For a given number of concurrent

1. Technically, PSs that start on different days are staggered. This is the convention adopted in this report. However, if the starts of PSs are on different days but the length of the separations are not large enough to impact troop or materiel deployment, then the PSs may be treated as if they started on the same day. This decision should be made on a case by case basis.

scenarios P, $P!$ sequences need to be evaluated. For large values of P, the amount of time may become exorbitant. Also, defence planning studies may involve hundreds of capabilities and thousands of PS combinations. As such, even in situations where the time needed to evaluate each set of $P!$ sequences may be small, the ability to conduct a complete analysis in a reasonable amount of time would be greatly enhanced by reducing the number of sequences studied for each capability for each combination of PSs. Furthermore, while staggering the starts of the scenarios leads to the reduction in the level of capability required to be deployed with short notices, there is no evidence that it will actually reduce the overall quantity of the capability required in all instances.

1.1 Aim

This report assesses the propriety of using orthogonal arrays (OAs), which are used widely in the field of robust design, to identify the subset of sequences that have to be evaluated to determine the most stringent requirement for which the military should plan and to verify that staggering the starts of the PSs leads to reduced capability requirements.

1.2 Scope

Capability requirements must be satisfied by a military with any combination of properly planned, organized, equipped, trained, and exercised personnel. The main objective of defence planning is to determine if a military is capable of providing these forces if required to do so. However, this report does not address the issue of how real-world forces would be deployed to satisfy capability requirements.

The remainder of the report is organised as follows. The development of a set of recursive equations to calculate the generic requirement given a particular PS sequence is presented in the next section. The use of OAs to reduce the number of sequences analysed is also presented in that section. Sample case studies are presented and discussed in Section 3. Section 4 contains the concluding remarks.

2 Determining Generic Capability Requirements

Capability requirements in PSs may be specified on a daily basis or aggregated for each month or any appropriate time frame. This time frame must be selected based on the specific characteristics of the planning problem at hand. Also, as indicated earlier, actual real-world forces must be used to provide the required capabilities. These forces are often deployed to an operation (PS) for a period of time and then rotated out for a period of time before being redeployed if required. The length of the deployment would depend on a number of factors including the capability and the type of operation; for some operations, forces are never rotated out.

In order to simplify the presentation and analysis in this report, it is assumed that:

- Time is measured in steps of one month;
- A rotation period is equivalent to three months;
- Capability requirements are specified for each rotation period. This corresponds to the highest single day requirement over the period;
- Units are on an ABC rotation pattern, that is, they have a six month break between successive deployments;
- All forces deployed would be available for redeployment in the next deployment period to which they can be deployed;
- The required capability is assumed to be delivered at the start of a period; and
- The separation between the start times of successive PSs is assumed to be the same for all PSs.

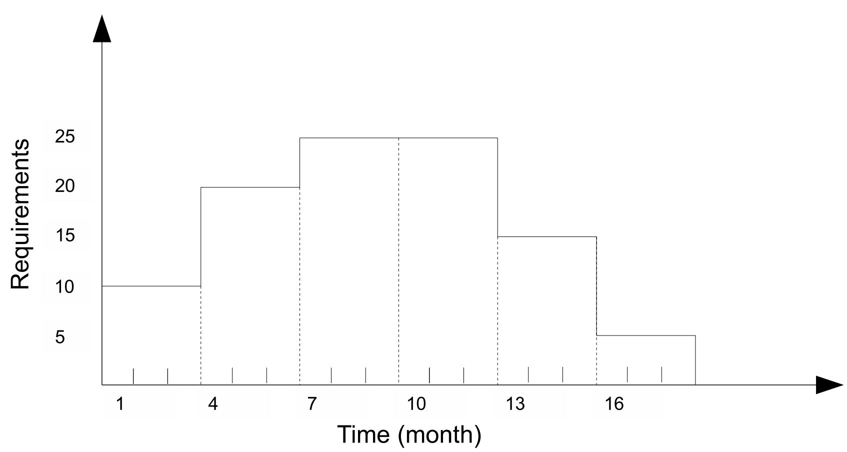


Figure 1: Capability Requirement Profile for a Single Planning Situation.

Figure 1 shows the capability requirements for a sample PS based on the stated assumptions. The PS is assumed to last 6 rotation periods, i.e., 18 months. Summing the requirements for each period, the total requirement is determined as 100. The requirements calculations are shown in Table 1. This assumes that each capability requirement is fulfilled with a new set of forces, i.e., those not previously deployed. However, given that the forces are on an ABC rotation, it is possible to reuse some of the forces deployed in the initial rotation in the fourth period and those in the second period in the fifth period, and so on.

Table 1: Total Requirements.

Rotation Period	Period Requirement	Total Requirement
1	10	10
2	20	30
3	25	55
4	25	80
5	15	95
6	5	100

Figure 2 depicts the impact of force rotation on the total requirements. As can be seen in the figure, at any given period beyond the third period, the reappearing forces may or not be enough to meet the requirements in that period. When more reappearing forces than needed are available, they may be held over and used at a later time or used in a different PS, in the case of concurrent operations. In the fourth period, the reappearing forces are not enough and therefore new forces are deployed together with the reappearing forces. In the fifth and sixth periods, there is a surplus of reappearing forces and no new forces are required. As such, the total generic requirement is 70; 30% less than the sum of the individual requirements. Table 2 shows a summary of how this is determined.

Table 2: Determining New Forces Required for Each Rotation Period.

Rotation		Reappearing Forces		
Period	Requirement	Available	Used	New Forces
1	10	0	0	10
2	20	0	0	20
3	25	0	0	25
4	25	10	10	15
5	15	20	15	0
6	5	30	5	0
				Total=70

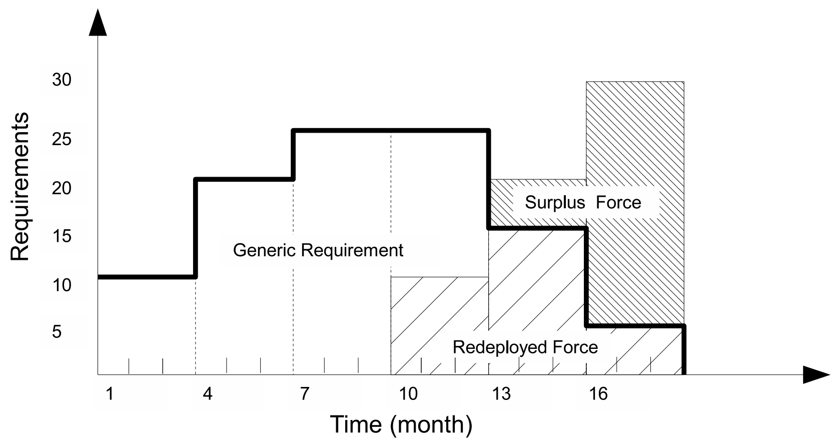


Figure 2: Illustration of Surplus and Reappearing Capability.

2.1 Requirements for Concurrent Operations

Figure 3 is an illustration of three PSs of different durations and possibly, with different capability requirement profiles, that are executed over a period of T months. PS 3 starts first at time $t = 1$ followed by PS 1 at $t = w + 1$ and then, PS 2 at $t = 2w + 1$. Note that the sequence (PS 3, PS 1, PS 2) is just one of six possible sequences: (PS 1, PS 2, PS 3), (PS 1, PS 3, PS 2), (PS 2, PS 1, PS 3), (PS 2, PS 3, PS 1,), (PS 3, PS 1, PS 2) and (PS 3, PS 2, PS 1).

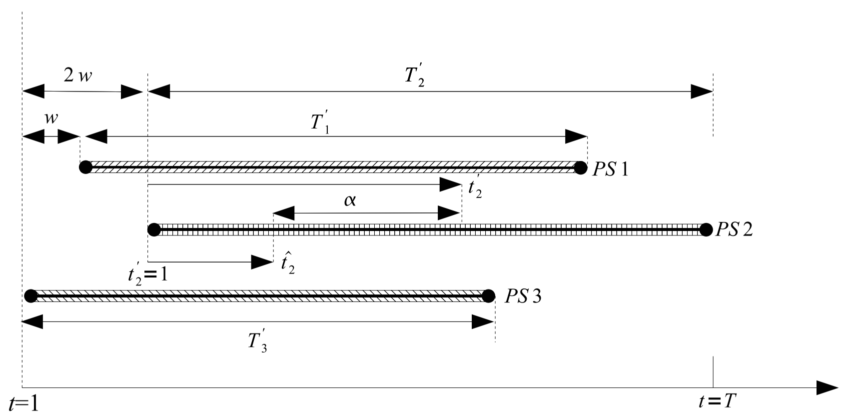


Figure 3: Illustration of Temporal Elements for Three Concurrent Planning Scenarios.

The requirements in the first period for PS 1 and PS 2 would appear at $t = w + 1$ and $t = 2w + 1$, respectively. Similarly, if there are more than 3 PSs, then the requirements for each PS starting at a later time would be offset by the time between the start of that PS and the very first one. As such, given P PSs and a starting sequence $s = (\phi_1, \phi_2, \ldots, \phi_p, \ldots, \phi_P)$, where ϕ_p is the starting order of PS p, the total new requirements that have to be satisfied at a time t, is given by the sum across all PSs at that time. That is:

$$r_t = \sum_{p=1}^{P} c_{t'_p} \tag{1}$$

with

$$t'_p = t - (\phi_p - 1) \cdot w$$

and

$$c_{t'_p} = 0, \quad \text{if } T'_p < t'_p \vee t'_p < 1$$

where

t	time step relative to the start of the first PS (months),
t'_p	time step relative to the start of a PS p (months),
p	index of the planning scenarios;
P	total number of concurrent PSs;
r_t	sum of new requirements at time step t;
$c_{t'_p}$	the capability requirement in PS p at time step t'_p;
ϕ_p	order of start of PS p, $\phi_p = 1, 2, \ldots P$ and $\phi_3 = 5$ implies that PS 3 is the fifth PS to start;
T'_p	total duration of PS p (months); and
w	time between starts of successive PSs.

The cumulative requirement at time t, R_t, is the sum of the requirement from the first month to time, t. That is:

$$R_t = \sum_{i=1}^{t} r_i = (R_{t-1} + r_t) \tag{2}$$

where $R_0 = 0$ and similarly, all variables have a value of zero at time step zero.

As illustrated in Figure 3 for PS 2, at time t'_2, capabilities that were deployed at an earlier time $\hat{t}_2$, would be available for redeployment. That is, for each individual PS, the amount of reappearing capability at a given time t'_p is given by

$$z_{t'_p} = \begin{cases} c_{\hat{t}_p}, & \text{if } (T'_p > \hat{t}_p > \alpha) \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

with $\hat{t}_p = t'_p - \alpha$, where

$z_{t'_p}$	amount of a capability available for redeployment at time step t as a result of it being previously deployed to PS p; and
α	length of rotation cycle (month) (e.g., α=9 for ABC rotation pattern with three month rotation periods)

The total amount of reappearing forces at time t is given by

$$y_t = \sum_{p=1}^{P} z_{t'_p}. \quad (4)$$

The cumulative amount of reappearing forces Y_t, is thus given by

$$Y_t = \sum_{i=1}^{t} y_i = (Y_{t-1} + y_t). \quad (5)$$

At any given time t, the difference between the cumulative requirement and the cumulative reappearing forces is the cumulative generic requirement, G_t. If this value is less than or equal to the cumulative generic requirement at time $t-1$, then $G_t = G_{t-1}$. This is the amount of generic capability required to meet the requirements up to time t and is given by,

$$G_t = \begin{cases} R_t - Y_t, & \text{if } (R_t - Y_t > G_{t-1}) \\ R_1, & \text{if } t = 1 \\ G_{t-1}, & \text{otherwise} \end{cases}. \quad (6)$$

Equations 2, 5 and 6 are recursive in nature and should therefore be applied starting with $t = 1$ and ending with $t = T$. G_T gives the (total) generic requirement for all P PSs with T defined as:

$$T = \max_{p \in \{1,2,\cdots P\}} \{T_p + (\phi_p - 1) \cdot w\}.$$

It should be noted that the equations are universally applicable irrespective of how time is measured. That is, the smallest time unit could be days, weeks or months, etc. The most important requirement is that the unit of measure should be such that the separation and the rotation periods can be specified as integer multiples of the smallest time unit.

Allowing for a slight abuse of notation and omitting the subscript T, the generic requirement given a sequence s is defined as $G(s)$. The objective of determining the most demanding requirement is in essence that of determining the optimal sequence s^* such that $G(s^*) \geq G(s)$ for all $s \in S$. The complete enumeration approach would apply the equations to every $s \in S$ and the s giving the highest $G(s)$ assigned to s^*. However, as stated earlier, this could be time consuming and the time required may be reduced by only considering $s \in S_o$, where $S_o \subset S$ and $|S_o| << |S|$ and determining the sequence s_o^*, such that $G(s_o^*) \geq G(s)$ for all $s \in S_o$. In this report, the contents of S_o are determined from standard OAs which are discussed below. In the remainder of this report, G and G_o are used to denote the generic requirements corresponding to s^* and s_o^*, respectively.

2.2 Orthogonal Arrays

The simplest approach to study the effect different levels of a number of factors/variables have on an outcome would be to investigate all possible combinations of the levels of the factors. That is, to conduct the factorial experiment. Unfortunately, this can sometimes be time consuming and/or expensive. It may therefore be more reasonable to make observations of the outcome at only some of the level combinations. Such experiments are called "fractional factorial" experiments and an OA may be employed to select the level combinations for the experiment.

Let B be the set of b levels. An $N \times k$ array D with entries from B is said to be an OA with k factors, b levels, strength f and index ρ (for some f in the range $0 \leq f \leq k$), if every $N \times f$ subarray of D contains each f-tuple based on B exactly ρ times as a row [4]. Such an OA is often designated as OA(N, k, b, f). [2] Note that this definition of “orthogonal” is different from the more general meaning of perpendicular: two vectors are orthogonal if their inner product is zero.

Although OAs have interesting mathematical properties and have been actively researched since they were discovered by Fisher [5] and Tippet [6], the main applications of OAs are in planning experiments [4]. Taguchi’s robust design method [7] is one such application and perhaps the most popular. The robust design method provides designers with a systematic and efficient approach for determining near optimum settings of design parameters [8, 9] by employing OAs of strength two.

Standard OAs are available from [10], [11] and [4] amongst many other sources. [3] Each array is meant for a specific number of independent factors and levels. For example, to conduct an experiment with six independent factors (A, B, C, D, E and F) with each factor having five levels (1, 2, 3, 4 and 5), the OA(25,6,5,2) array shown in Table 3 may be used. This has a strength of two and requires only 25 experiments. A factorial design would require $5^6 = 15625$ experiments and can be viewed as an OA of strength k (6 in this case). Note that the assignment of the factors to the columns may be different from what is specified in Table 3. For example, factor A could have been assigned to the third column and factor C to the first. The purpose of using an OA of strength two (similarly, k), is to study the effects of the interaction between any two (similarly, k) factors, and reordering the factors has no impact on that.

2. This designation does not include ρ because it can be derived from the other parameters. Specifically, $\rho = N/b^k$. Other common designation used for OAs are $L_N(b^k)$, OA(N, b^k, f), OA(b, k, ρ) and $OA_\rho(f, k, b)$.

3. The orthogonal arrays used in this report are from these sources.

Table 3: The OA(25,6,5,2) Orthogonal Array.

Experiment	Factors					
	A	B	C	D	E	F
1	1	1	1	1	1	1
2	1	2	3	4	5	2
3	1	3	5	2	4	3
4	1	4	2	5	3	4
5	1	5	4	3	2	5
6	2	1	5	4	3	5
7	2	2	2	2	2	1
8	2	3	4	5	1	2
9	2	4	1	3	5	3
10	2	5	3	1	4	4
11	3	1	4	2	5	4
12	3	2	1	5	4	5
13	3	3	3	3	3	1
14	3	4	5	1	2	2
15	3	5	2	4	1	3
16	4	1	3	5	2	3
17	4	2	5	3	1	4
18	4	3	2	1	5	5
19	4	4	4	4	4	1
20	4	5	1	2	3	2
21	5	1	2	3	4	2
22	5	2	4	1	3	3
23	5	3	1	4	2	4
24	5	4	3	2	1	5
25	5	5	5	5	5	1

Each row in Table 3 represents the setting of the factors for an experiment. For example, the fourth experiment is conducted by keeping factor A at level 1, factor B at level 4, factor C at level 2, factor D at level 5, factor E at level 3, and factor F at level 4. For the PS sequencing application, an experiment corresponds to a specific starting sequence, the factors correspond to the PSs, and the levels are the order of start of the PSs. Since a PS can only have P possible positions in a sequence of P PSs and no two PSs may start on the same day, the number of factors should correspond to the number of levels and a level cannot be repeated in a sequence. Consequently, the OA in Table 3 cannot be used for the problem studied in this report without modifications. To modify OA(25,6, 5,2) for the 5-PS case, one column (e.g. that for factor F) is discarded and certain rows ignored; in this instance, rows 1, 7, 13, 19 and 25. Table 4 shows the modified OA. It has 20 rows and exactly five columns corresponding to the five PSs. Note that in the strict

Table 4: The Modified OA(25,6,5,2) Orthogonal Array.

Original	Factors				
Experiment	A	B	C	D	E
2	1	2	3	4	5
3	1	3	5	2	4
4	1	4	2	5	3
5	1	5	4	3	2
6	2	1	5	4	3
8	2	3	4	5	1
9	2	4	1	3	5
10	2	5	3	1	4
11	3	1	4	2	5
12	3	2	1	5	4
14	3	4	5	1	2
15	3	5	2	4	1
16	4	1	3	5	2
17	4	2	5	3	1
18	4	3	2	1	5
20	4	5	1	2	3
21	5	1	2	3	4
22	5	2	4	1	3
23	5	3	1	4	2
24	5	4	3	2	1

sense of word, this is not orthogonal since for any two columns, combinations with similar levels (i.e., (0,0), (1,1), (2,2), (3,3), (4,4) and (5,5)) are not permitted.

The economy of run size afforded by the OA-based fractional factorial design may come at a cost. Recall that, the OA in Table 4 has strength of two. As such, the result is not guaranteed to be the same as that which would be obtained using an OA of higher strength or the complete set of factorial sequences, but may be close. Two metrics are therefore proposed to measure the propriety of using S_o instead of S. These are:

$$\textit{Rank Dominance} \;\; \gamma = d/P! \tag{7}$$

and

$$\textit{Relative Deviation} \;\; \delta = \frac{(G - G_o)}{G} \times 100\% \tag{8}$$

Rank Dominance is the ratio of the number (d) of sequences in S for which $G(s) \leq G_o$ and the *Relative Deviation* measures how close G_o is to G. The value $1-\gamma$, is a measure of the risk inherent in using G_o for planning. The closer γ is to 1 and δ is to *zero*, the more appropriate the use of OAs.

3 Case Studies

To test the suitability of using OAs as outlined previously in generic requirements analysis, a number of sample cases with different capability requirement profiles were analyzed. A Monte Carlo simulation was employed to randomly specify the characteristics of the PSs. The methodology is illustrated first with a single 5-PS case and then more detailed results and analyses are presented for a number of 8-PS cases.

3.1 The Simulation Procedure

In generating the set of concurrent PSs, firstly, the length of each scenario was determined randomly; it was assumed to be more than nine months but less than 18 months. Requirements were then randomly generated and assigned to each period of the PS using a uniform random number generator such that they are all less than or equal to a predetermined maximum value. Four different runs were done with each run consisting of 2000 iterations. Each run had a different limit on the maximum requirement within a period for each PS. Table 5 shows the maximum requirements for the four runs. In the "mixed" run, the maximum requirement was not set to a specific value but rather, each PS had its maximum requirement chosen randomly to be one of the other three values.

Table 5: Limits on the Maximum Capability Requirements in a Period for each PS.

Run	Maximum Requirement
1	Mixed
2	10
3	20
4	200

At each iteration, a new case (set of PSs) was randomly generated and the following values calculated: G_o^1, G_o^2 and G_o^3 (based on S_o); G^1, G^2 and G^3 (based on S); and G^0. The superscripts $0,1,2$ and 3 refer to the PS separation in months (i.e., $w = 0,1,2,3$ in Equation 1). As such, G^0 refers to the special case where all the PSs are started on the same day. The OA in Table 4 was used for the 5-PS case and the OA shown in Table 6 used for the 8-PS cases. Table 6 is a modified version of OA(64,9,8,2) and has 56 sequences instead of 40320 for the full factorial design, i.e., $|S_o| = 56$ and $|S| = 40320$.

Table 6: Modified Orthogonal Array for 8 PSs.

	Planning Scenario Order									Planning Scenario Order							
Trial	PS 1	PS 2	PS 3	PS 4	PS 5	PS 6	PS 7	PS 8	Trial	PS 1	PS 2	PS 3	PS 4	PS 5	PS 6	PS 7	PS 8
1	1	2	3	4	5	6	7	8	29	5	1	2	6	4	8	7	3
2	1	3	5	7	6	8	2	4	30	5	2	4	7	8	3	1	6
3	1	4	7	6	2	3	8	5	31	5	3	6	4	7	1	8	2
4	1	5	6	2	8	4	3	7	32	5	4	8	1	3	6	2	7
5	1	6	8	3	4	7	5	2	33	5	6	7	8	1	2	3	4
6	1	7	2	8	3	5	4	6	34	5	7	1	3	2	4	6	8
7	1	8	4	5	7	2	6	3	35	5	8	3	2	6	7	4	1
8	2	1	4	3	6	5	8	7	36	6	1	3	8	7	4	2	5
9	2	3	8	5	1	4	7	6	37	6	2	1	5	3	7	8	4
10	2	4	6	8	5	7	1	3	38	6	3	7	2	4	5	1	8
11	2	5	7	4	3	8	6	1	39	6	4	5	3	8	2	7	1
12	2	6	5	1	7	3	4	8	40	6	5	8	7	2	1	4	3
13	2	7	3	6	8	1	5	4	41	6	7	4	1	5	8	3	2
14	2	8	1	7	4	6	3	5	42	6	8	2	4	1	3	5	7
15	3	1	7	5	8	6	4	2	43	7	1	8	2	5	3	6	4
16	3	2	5	8	4	1	6	7	44	7	2	6	3	1	8	4	5
17	3	4	1	2	7	8	5	6	45	7	3	4	8	2	6	5	1
18	3	5	4	6	1	7	2	8	46	7	4	2	5	6	1	3	8
19	3	6	2	7	5	4	8	1	47	7	5	3	1	4	2	8	6
20	3	7	8	4	6	2	1	5	48	7	6	1	4	8	5	2	3
21	3	8	6	1	2	5	7	4	49	7	8	5	6	3	4	1	2
22	4	1	6	7	3	2	5	8	50	8	1	5	4	2	7	3	6
23	4	2	8	6	7	5	3	1	51	8	2	7	1	6	4	5	3
24	4	3	2	1	8	7	6	5	52	8	3	1	6	5	2	4	7
25	4	5	1	8	6	3	7	2	53	8	4	3	7	1	5	6	2
26	4	6	3	5	2	8	1	7	54	8	5	2	3	7	6	1	4
27	4	7	5	2	1	6	8	3	55	8	6	4	2	3	1	7	5
28	4	8	7	3	5	1	2	6	56	8	7	6	5	4	3	2	1

3.2 Discussion of Results

The results for the 5-PS case are presented first to illustrate how the PSs are generated and how the performance metrics are calculated. This is followed by a more extensive discussion using a number of 8-PS cases.

3.2.1 Sample 5-PS Case

Table 7 shows the randomly generated capability requirements for a 5-PS case. The maximum demand in a period was restricted to 10 (Run 2). The PSs have different durations with PS 4, the shortest, lasting three periods (nine months) and PS 3, the longest, lasting 6 periods. Using equations 1-6, optimal sequences s_o^* and s^*, and the corresponding generic requirements were determined. Table 8 shows a summary of the results. Similar generic requirements were obtained for the 1- and 2-month separation, i.e., $G_o^1 = G^1$ and $G_o^2 = G^2$. On the other hand, different values were obtained for the 3-month separation, $G_o^3 \neq G^3$. However, the difference was not significant. The *Relative Deviation* (δ) was just 0.07 (7%) and the *Rank Dominance* (γ) was equal to 0.93. That is, there is a 7% $(100 - 0.93 \times 100)$ risk of not being able to meet future requirements if G_o is used for planning.

Table 7: Capability Requirements for the Sample 5-PS Case.

	Planning Scenarios				
Period	PS 1	PS 2	PS 3	PS 4	PS 5
1	8	3	4	5	5
2	2	2	4	5	5
3	7	2	3	5	5
4	6	2	4	0	4
5	1	0	4	0	4
6	0	0	3	0	0

Table 8: Results for the Sample 5-PS Case.

PS Separation	G_o	G	s_o^*	s^*	γ	δ
1	64	64	(3, 2, 1, 5, 4)	(5, 4, 2, 3, 1)	1	0
2	62	62	(5, 3, 1, 4, 2)	(5, 3, 2, 4, 1)	1	0
3	55	59	(3, 2, 1, 5, 4)	(3, 5, 1, 4, 2)	0.93	7%

Note that although $G_o^1 = G^1$ and $G_o^2 = G^2$, the corresponding sequences s_o^* and s^* are different. This is simply because different sequences may give rise to the same level of capability requirement.

3.2.2 Sample 8-PS Cases

The results of the 8-PS cases are presented with a focus on the mixed run (Run 1). As stated earlier, 2000 iterations were used for each run. At each iteration, a set of eight PSs (case) were randomly generated and the generic requirements, G_o and G, determined for separation times of one, two, and three months between the start of the PSs. On the average, the time (0.27 ms) to determine G_o was 99.8% lower than the time (196.6 ms) to determine G.

Mixed Run (Run 1)

Figure 4 shows a plot of the *Relative Deviations* for the cases in Run 1. For each *Relative Deviation*, the graph gives the number of cases that had *Relative Deviations* less than that value. As is evident from Figure 4, the larger deviations were observed when the PS separation was three months. While only 10 cases had deviations in excess of 3% when the separation was one month, those for the 3-month separation were mostly (1180 of 2000) above 3% with the highest deviation being 15.75%.

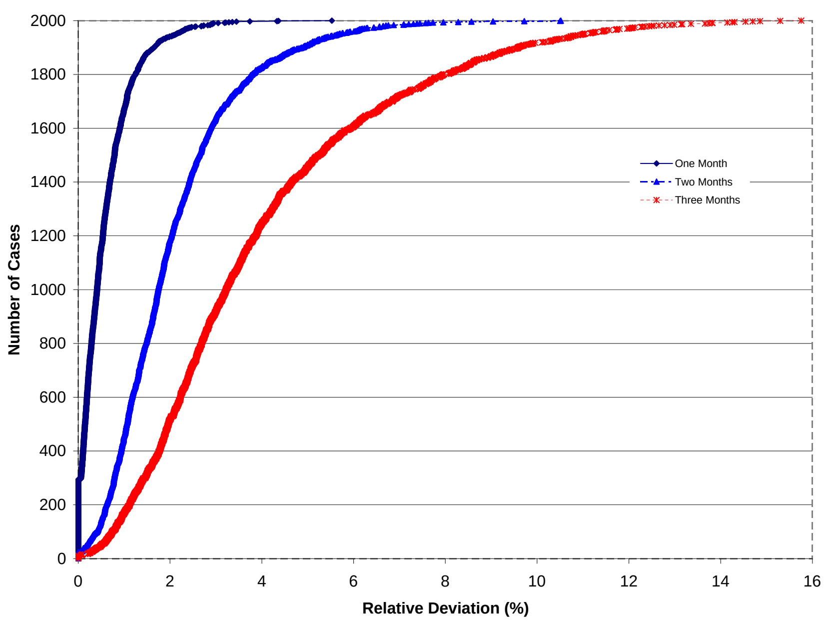


Figure 4: Relative Deviations for Cases in Run 1 for PS Separations of 1, 2, and 3 Months.

Figure 5 shows the distribution of the *Rank Dominance* for the three separation times studied. In spite of the disparities observed in the *Relative Deviation* values, the *Rank Dominance* values seem to have similar dispersions with those for separations of 2 and 3 months being almost identical. The chart also shows that the minimum value of the *Rank Dominance* was approximately 0.92. This implies that if the G_o is used in place of G, at worst, it would be enough in 92% of all possible future occurrences.

Table 9 shows a number of representative percentiles. Over 50% of the cases had a *Rank Dominance* in excess of 0.99. The *Rank Dominance* exceeded 0.98 (25th percentile) and .995 (75th percentile) in 75% and 25% of the cases, respectively. There is a higher likelihood that $G_o = G$ when the separation is shorter. For a 1-month separation, 14.7% of the cases had $G_o = G$ corresponding to $\delta = 0$ in Figure 4. The corresponding values for 2- and 3-month separations were only 0.95% and 0.65% respectively. These are negligible but as seen in Table 9, the corresponding values for the 75% percentile are quite high.

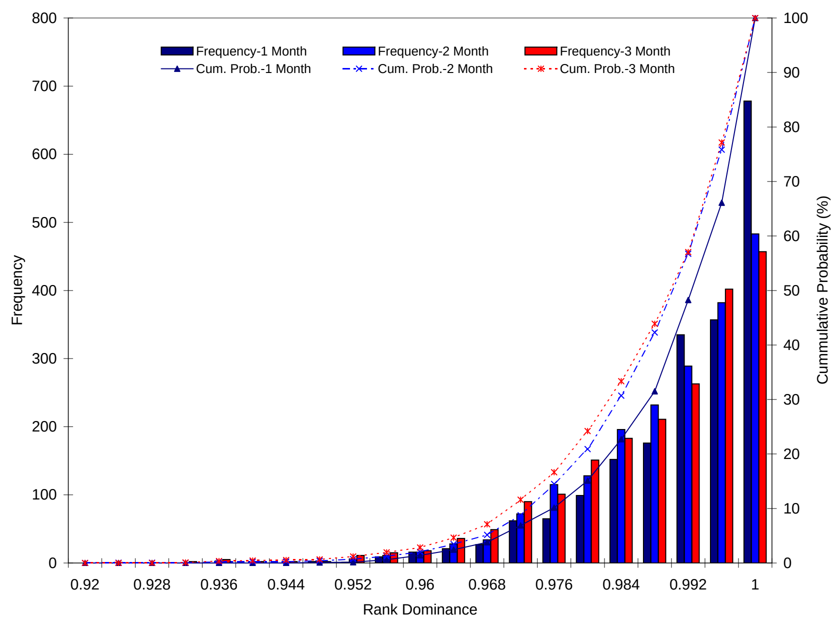


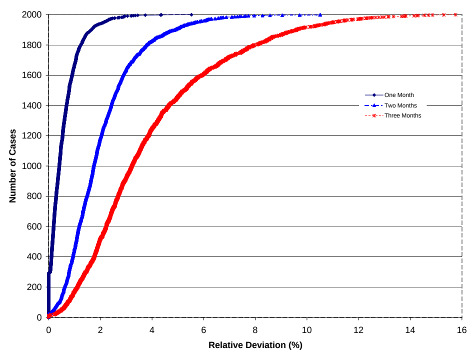
Figure 5: Frequency and Cumulative Distributions for the Rank Dominance for Run 1 for PS Separations of 1, 2, and 3 Months.

Table 9: Rank Dominance Values for Representative Percentiles for Run 1.

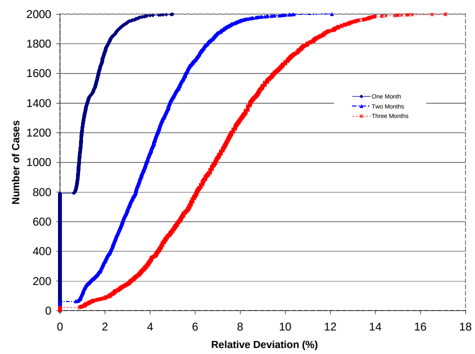
PS Separation	Percentile		
	25th	50th	75th
1	0.9851	0.9929	0.9982
2	0.9819	0.9903	0.9958
3	0.9804	0.9900	0.9956

All Runs

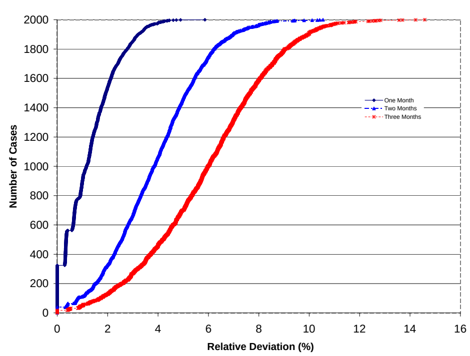
Figure 6 shows the *Relative Deviation* plots for all the runs. For PS separation of one month, the *Relative Deviation* did not exceed 6.1% which was recorded for Run 4. With a 2-month separation, *Relative Deviations* greater than 11% were observed only in Run 2. However, with a 3-month separation, all of the runs had some *Relative Deviations* greater than 11% but only Run 2 had *Relative Deviations* greater than 16%. However, for all PS separations, the number of cases with *Relative Deviation* equal to zero is greatest for Run 2, followed by Runs 3, 1 and 4, in that order. The foregoing points to the fact that no definitive conclusions can be made about the relation between the deviation and the order of magnitude of the requirements.



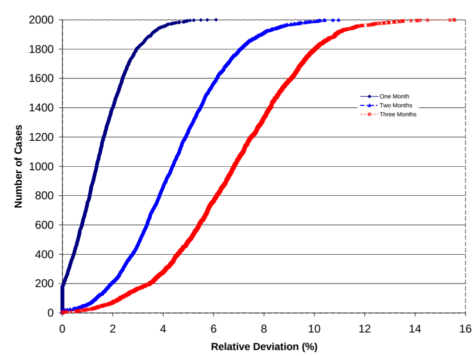
(a) Run 1



(b) Run 2



(c) Run 3.

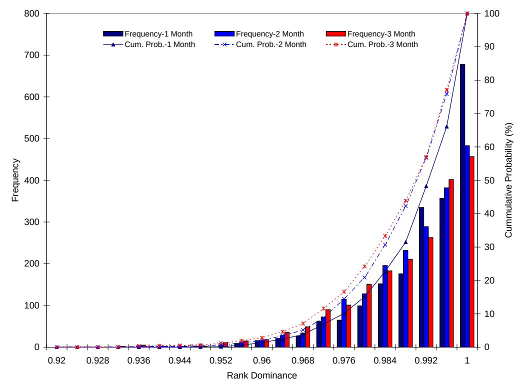


(d) Run 4.

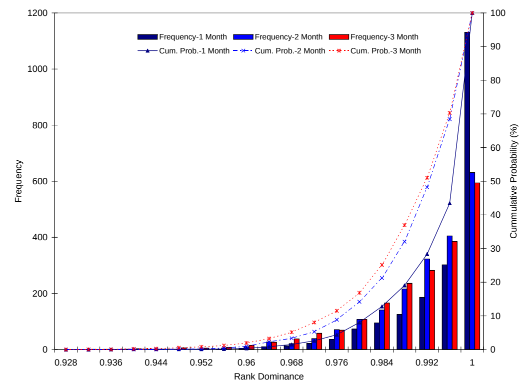
Figure 6: Comparison of Relative Deviations for all Runs for PS Separations of 1, 2, and 3 Months.

The worst *Relative Deviation* was 17.1% and all but 13 out of 24,000 (2000 Cases $\times$ 3 PS Separations $\times$ 4 Runs) cases were below 15%. That is, using the OA based approach underestimated the required capability by only 17.1% at the most, and only in 13 cases was the underestimation greater than 15%.

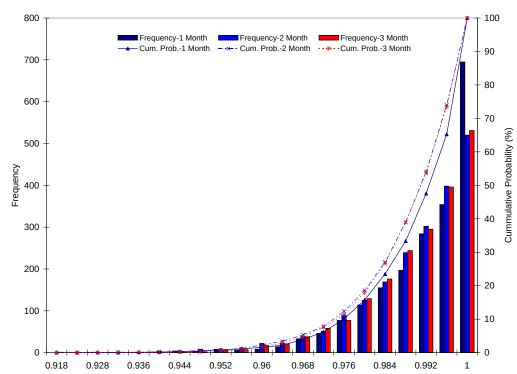
The cumulative distributions and histograms of the *Rank Dominance* for all the runs are shown in Figure 7. Again, these point to the possibility that reasonable results can be obtained using OAs. As the cumulative distributions in Figures 7b, 7c and 7d show, the impact of the PS separation diminishes as the magnitude of the requirements increases. Table 10 shows the percentage of cases for each run and PS separation that had a *Rank Dominance* of one, i.e. $G_o = G$. These percentages decrease with increasing PS separation. They ranged between 0.8% and 3.05% for a 2-month separation but were less than 1.05% for a separation of three months. Although these are very small, as evidenced by the last set of bars on the charts, a significant number of the cases have *Rank Dominance* greater than 0.996 for all the runs and PS separations.



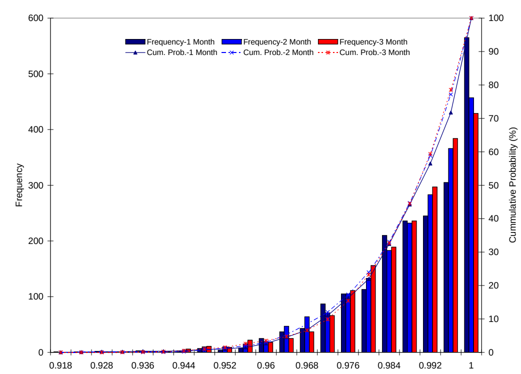
(a) Run 1.



(b) Run 2.



(c) Run 3.



(d) Run 4.

Figure 7: Comparison of Rank Dominance Cumulative Distribution and Frequency for all Runs for PS Separations of 1, 2, and 3 Months.

Table 10: Percentage of Cases for which the Generic Requirements from both Approaches were Equal (i.e., $G_o = G$) for All Runs.

PS Separation	Run 1	Run 2	Run 3	Run 4
1	14.7	39.6	16.2	9.45
2	1.2	3.05	1.9	0.8
3	0.6	1.05	0.85	0.2

Impact of Same-Day Starts

As indicated earlier, there is the perception that the most demanding total requirement arises when all the operations start on the same day. Table 11 shows a comparison of G^1, G^2 and G^3 with G^0 for the four runs. As can be seen from the table, this perception is not always borne out but the longer the PS separation, the more likely it is to be true.

Table 11: Number of Cases for which the Same-Day Start Generic Requirement Exceeded the Staggered Start Generic Requirement.

PS Separation	Run 1	Run 2	Run 3	Run 4
1	242	192	852	298
2	845	1552	1981	1690
3	1595	2000	2000	2000

3.3 Further Application

The PS portfolios used for defence planning often consist of a large number of PSs that are categorised into groups. The level of ambition specifies the number of PSs from each group that may be undertaken concurrently with PSs from other groups. The set of legal combinations is formed by determining all possible combinations based on the level of ambition. This study only looked at the impact the sequencing of one of these possible combinations had on the capability requirement. However, a relevant question in defence planning is to determine the particular combination of scenarios, amongst all the possible combinations, that gives the sequence with the greatest capability requirement.

In some instances, the number of possible PS combinations can be in the tens of thousands. It will therefore be incomprehensible to evaluate all sequences for all combinations. To circumvent this, a two stage approach is often employed. In the initial stage, all scenarios are deemed to start on the same day and the most demanding combination determined. That is, the sequencing of the scenarios are ignored.

The most demanding combination is then used in the second phase to determine the most extreme sequence for that specific combination. Apart from the fact that the assumption in the first stage calculation is unrealistic (no military would start all operations on the same day), there is no guarantee that the combination determined in this stage gives the most demanding PS sequencing. Yost [12] suggested the use of OAs for the first stage to reduce the number of combinations. However, no results were presented to justify the approach.

In robust design, a typical Taguchi experiment consists of a design matrix or inner array which specifies the settings of the factors within the control of the designer, and a noise matrix or outer array which specifies the uncontrollable factors that affects the performance of the system. The two arrays are then crossed, so that every combination of control factors in the inner array takes place at every condition called for by the outer array of noise factors. This approach could similarly be applied to defence planning with the PS combinations analogous to the noise factors and the PS start order, analogous to the design factors.

Table 12: The Inner Array Representation for PS Combination.

	PS Type				
Combination	I	II	III	IV	V
1	a	a	a	a	a
2	b	a	a	b	b
3	a	b	a	b	a
4	a	a	b	a	b
5	b	b	a	a	b
6	b	a	b	b	a
7	a	b	b	b	b
8	b	b	b	a	a

As an illustration, assume that there are five types of PSs and for each type, there are two defined in the PS portfolio; one ‘a’, is undertaken under say, austere conditions and the other ‘b’, under non-austere conditions. If the level of ambition calls for the ability of the military to undertake five concurrent operations; one of each PS type, then the total number of possible combinations is $2^5 = 32$. This may be reduced to eight using an OA. The relevant OA is shown in Table 12. This may be set as the outer array. Since there are five PSs involved, Table 4 can be used as the inner array. For determining the most robust capability requirement specification, the 20 sequences in Table 4 are applied to each combination of Table 12. In essence, 20 sequences are used for each of the eight combinations instead of considering all 120 (5!) sequences for each of the 32 PS combinations.

4 Conclusions

Determining the levels of capabilities a military should maintain for future operations is an important aspect of defence planning. This is more so when the military intends to undertaken multiple operations concurrently. This report proposed a set of recursive mathematically expressions for calculating the capability requirements regardless of the force rotation pattern and suggested the use of OAs to reduce the effort needed in the planning process.

A Monte Carlo simulation was used to generate PSs to illustrate the utility of using OAs in place of factorial experiments to determine the most demanding planning scenario starting order. Four different runs with different limits on the maximum requirements were studied. For each run, 2000 cases, with each case consisting of a different set of PSs were randomly generated. For each case, PS separation lengths of one, two and three months were considered. In all cases, the OA was shown to perform very well based on the performance metrics defined irrespective of the length of PS separation. In the worst performing case, the capability requirements specification based on the OA exceeded the requirements for at least 91.8% (as measured by the *Rank Dominance*) of all possible sequencing of the PSs. The worst *Relative Deviation* was 17.1% and all but 13 out of 24,000 (2000 Cases $\times$ 3 PS Separations $\times$ 4 Runs) cases were below 15%. That is, using the OA based approach underestimated the required capability by only 17.1% at the most, and only in 13 cases was the underestimation greater that 15%.

Although using an OA reduced the time for the analysis by more than 99%, the time (an average of 192 ms for each case) needed for the complete enumeration of all the sequences was also reasonable. Given a large number of capabilities and PS combinations, this time reduction can lead to larger overall time savings. Also it was shown that staggering the starts do not necessarily lead to reduced requirements although the possibility of a reduction in the requirement increases with increasing PS separation time.

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List of abbreviations

CBP	Capability Based Planning
ms	milliseconds
OA	Orthogonal Array
PS	Planning Scenario

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The basis of defence planning has in the past few years shifted from large single conventional wars to that of preparation for concurrent operations in multiple theatres. Planners often assume that future operations would have staggered starts. This assumption makes the sequence in which the operations are executed consequential with respect to the levels of capabilities needed to meet requirements. Often times, the most demanding sequence is determined by conducting a complete enumeration of all possible sequencing of the planning scenarios. The most stringent capability requirement so determined is then used for planning. This report provides results of a simulation study that shows that it is possible to get a requirement specification that is adequate for over 92% of all future possibilities using considerably fewer sequences based on orthogonal arrays (56 instead of 40320 sequences in the case of eight planning scenarios). It also shows that contrary to popular perception, staggering the starts of the operations does not necessarily lead to reduced requirements.

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