Optimizing Structure of Parallel Homogeneous Systems under Attack

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Abstract: A system of identical parallel elements has to be purchased and deployed. The cumulative performance of the elements must meet a demand. There are different types of elements characterized by their performance and cost in the market. We consider convex, linear, and concave relationships between performance and cost. The defender determines the system structure by choosing the type and the number of elements in the system. The defender distributes its limited resource between purchasing the elements and protecting them from outside attacks. The attacker chooses the number of elements to attack and distributes its limited resource evenly among all the attacked elements. The vulnerability of each element is determined by a contest success function between the attacker and the defender. The damage caused by the attack is associated with the cost of destroyed elements and the reduction of the cumulative system performance below the demand. The defender tries to minimize the damage anticipating the best attacker's strategy for any system structure. An algorithm for determining the optimal system structure is suggested. Illustrative numerical examples are presented.

Keywords: Production, reliability, risk, performance, cost, vulnerability, survivability, optimization, defense, attack, protection, game theory, homogeneous system

1. Introduction

Researchers attempting to use reliability theory to develop risk-reduction strategies have typically assumed a static threat [1-3]. In [4-5] it is assumed that the defender minimizes the success probability and expected damage of an attack (see also [6-7]). Levitin [8] determined the expected damage for any distribution of the attacker's and the defender's effort in complex multi-state systems. Several researchers have introduced human factors to analyze performability engineering. Renn and Sellke [9] drew on sociological and psychological research to consider risk governance, Kosmowski [10] introduced human factors into safety analysis, and Kuipers [11] balanced hard and soft issues for the performability of work teams.

The September 11, 2001 attack illustrated that major threats today involve strategic attackers. There is a need to proceed beyond earlier research and assume that both the defender and attacker of a system are fully strategic optimizing agents.

Following this approach [12] applied game theory to analyze components in isolation. See [13], for an analysis where one agent defends each component in a system, [14-15] for interdependence between components, and [16-18] for defense and attack of series and parallel systems, complex networks, and two-component multi-state systems.
The optimization of the resource distribution among different defense measures is an essential part of the defense strategy. Levitin [19] analyzed optimal resource distribution between camouflage and protection efforts, [20] applied false targets, [29] combined false targets with preventive strike, and [21] applied secrecy in defensive allocations to deter the attacker. Zhao [22] analyzed fault tolerance game theoretically, where the defender replicates to ensure high reliability and availability, and the attacker injects faults to reduce the reliability and/or availability. Reference [23] analyzed the defense resource distribution between two sequential attacks, and [24] considered a K-Round duel with uneven resource distribution.

Levitin and Hausken [25] analyzed the optimal distribution of resources between protection and redundancy in homogeneous parallel systems. This paper goes one step further to incorporate the choice of type of system elements. When the system is built from scratch, the defender usually has a list of elements available in the market and chooses the type of elements it purchases to build the system. The elements are characterized by their nominal performance and cost. The defender can purchase many low cost elements where each element has low performance or few expensive elements where each element has high performance. This decision depends on the relation between performance and element cost which we assume can be convex, linear, and concave. By choosing the type and the number of elements the defender determines the system structure. The remainder of the defender's budget is invested into protecting all system elements.

The article assumes that each element can either work with nominal performance or be completely destroyed (electronic devices, mechanical equipment etc.). This is realistic since multi-state systems that can work with different performance rates can usually be decomposed into two-state elements (for example, steam generator's capacity can vary depending on availability of heating sections which can be made dichotomous). Section 2 presents the model. Section 3 presents the minmax algorithm. Section 4 considers an Illustrative example. Section 5 concludes.

**Basic Definitions**

- **Element**: Lowest-level part of system, which is characterized by its vulnerability and performance
- **Performance**: Quantitative measure of task performing intensity of element or system (capacity, productivity, processing speed, task completion time etc.)
- **Vulnerability**: Probability of destruction
- **Demand**: Required level of performance
- **Unsupplied demand**: Difference between the demand and system performance in the case when the demand is not met
- **Protection**: Technical or organizational measure aimed at reduction of destruction probability of system elements in the case of attack

**Notation**

- \( R, r \): Attacker's and defender's resources
- \( T, t \): Attacker's and defender's effort per single element
- \( A, a \): Costs of attacker's and defender's effort unit
- \( m \): Contest intensity
- \( H \): Number of available types of system elements
- \( h \): Element type
- \( C(h) \): Cost of element of type \( h \)
2. Model

We consider a system that consists of identical parallel genuine elements (GEs) with the same functionality. There are \( H \) different types of elements available in the market. Each type \( h \) is characterized by its cost \( C(h) \) and nominal performance \( G(h) \). Given the defense budget \( r \), the defender decides how many and which type of elements it purchases and deploys. We assume that only one type is purchased (because of contracting and maintenance reasons). The total attacker's resource is \( R \), the total defender's resource is \( r \).

If the defender purchases \( N \) elements of type \( h \), it distributes the remaining budget \( r-C(h)N \) evenly among the elements and allocates it into protecting the elements such that the per-element protection resource is \( \frac{r}{N} - C(h) \), which gives the per-element protection effort \( t = \frac{r}{N} - C(h) \). The nominal cumulative system performance is \( NG(h) \). The attacker can attack \( Q \) out of \( N \) elements. In this case it achieves the per-target attack effort \( T = \frac{R}{Q} \) and can destroy from 0 to \( Q \) elements.

The vulnerability of any element is determined by a contest between the defender and the attacker. The contest is expressed as a contest success function modeled with the common ratio form [26] as

\[
v = \frac{T^m}{T^m + t^m},
\]

where \( \frac{\partial v}{\partial T} > 0, \frac{\partial v}{\partial t} < 0 \), and \( m \geq 0 \) is a parameter that expresses the intensity of the contest. If the attacker exerts high effort, he is likely to win the contest which gives high vulnerability. If the defender exerts high effort, he is likely to win the contest which gives low vulnerability. Since the agents have limited budgets, and separation is costly for the defender, there are limits to how high efforts the agents exert. When \( m=0 \), the efforts \( t \) and \( T \) have no impact on the vulnerability regardless of their size which gives 50% vulnerability. \( 0 < m < 1 \) gives a disproportional advantage of investing less than one's opponent. When \( m=1 \), the investments have proportional impact on the vulnerability. \( m>1 \) gives a disproportional advantage of investment more effort than one's opponent (economies of scale). Finally, \( m=\infty \) gives a step function where "winner-takes-all".

The parameter \( m \) is a characteristic of the contest which can be illustrated by the history of warfare. Low intensity occurs for components that are defendable, predictable, and where the individual ingredients of each components are dispersed, \( i.e., \) physically distant or separated by barriers of various kinds. Neither the defender nor the attacker can get a significant upper hand. An example is the time prior to the emergence of cannons and modern fortifications in the fifteenth century. Another example is entrenchment combined with the machine gun, in multiply dispersed locations, in World War I [27, pages 32-33]. High \( m \) occurs for components that are less predictable, easier to attack, and where the individual ingredients of each component are concentrated, \( i.e., \) close to each other or not separated by particular barriers. This may cause "winner-take-all" battles and dictatorship by the strongest. Either the defender or the attacker may get the upper hand. The combination of airplanes, tanks, and mechanized infantry in World War II allowed...
both the offense and defense to concentrate firepower more rapidly, which intensified the
effect of force superiority.

Having the vulnerabilities of system elements as functions of the attacker’s and the
defender’s efforts both agents can estimate the expected damage \( D \) caused by the attack
for any possible distribution of these efforts. The defender’s objective is to minimize the
expected damage using the fixed resource \( r \) for purchasing system elements and protecting
them. The attacker’s objective is to maximize the expected damage using the fixed
resource \( R \) for attacking the chosen \( Q \) elements. The damage \( D \), which the agents seek to
maximize and minimize respectively, is defined in the next section.

3. Minmax Algorithm

The system must meet a demand \( F \). If the attacker destroys \( k \) elements, the damage
caused by the attack is proportional to the cost of the destroyed elements and to the cost of
the system performance reduction below the demand:

\[
d(k) = \varepsilon \max\{0, F - G(h)(N - k)\} + kC(h),
\]

where \( \varepsilon \) is the cost of one unsupplied demand unit. Having the probability \( v \) of destruction
of each element in the case of attack on \( Q \) elements, one can obtain the expected damage
can be obtained as

\[
D = \sum_{k=1}^{Q} d(k) \left( \frac{Q}{k} \right)^k (1-v)^{Q-k} = \sum_{k=1}^{Q} \left( \varepsilon \max\{0, F - G(h)(N - k)\} + kC(h) \right) \left( \frac{Q}{k} \right)^k (1-v)^{Q-k}.
\]

The attacker’s per-element effort is \( R/QA \), the defender’s per-element protection
effort is \( (r-C(h)N)/(aN) \). Thus

\[
D(h,N,Q) = \sum_{k=1}^{Q} \left( \varepsilon \max\{0, F - G(h)(N - k)\} + kC(h) \right) \times \left( \frac{Q}{k} \right)^k (1-v)^{Q-k}.
\]

The defender builds the system over time. The attacker takes it as given when
choosing its attack strategy. Therefore, we analyze a two period minmax game where the
defender moves in the first period, and the attacker moves in the second period. The
defender’s two strategic choice variables are \( h \) and \( N \). The attacker’s one strategic choice
variable is \( Q \). This means that the defender chooses a strategy in the first period that
minimizes the maximum utility that the attacker can earn in the second period.
Mathematically, this means that we solve

\[
\min_{h,N} \max_{Q} D(h,N,Q).
\]

1. Assign \( D_{\text{minmax}} = \infty \);
2. for each \( h=1,\ldots,H \)

The system is built to meet a demand \( F \), which means that the inequality \( NG(h) \geq F \)
must hold for any \( h \). Therefore, the minimal number of elements in the system is \( \lceil F/G(h) \rceil \).
On the other hand the total resource needed to produce and deploy \( N \) GEs cannot exceed
\( r \cdot NC(h) \cdot cr \). So, the system can be produced and deployed only if the inequality
\( r \cdot C(h) \cdot F/G(h) \) holds for any given \( h \). The optimal values \( h,N,Q \) corresponding to the
minmax strategy (expressed with * after the variable) can be obtained by the following
enumerative procedure.

1. Assign \( D_{\text{minmax}} = \infty \);
2. for each \( h=1,\ldots,H \)
2.1. for each \( N = \left\lfloor F/G(h) \right\rfloor, \ldots , \left\lfloor r/C(h) \right\rfloor \)
   2.1.1. assign \( D_{\text{max}} = 0 \)
   2.1.2. for each \( Q = 1, \ldots , N \)
            obtain \( D(h,N,Q) \) using (4) and
            if \( D_{\text{max}} < D(h,N,Q) \) assign \( D_{\text{max}} = D(h,N,Q) \);
   2.1.3. if \( D_{\text{max}} < D_{\text{minmax}} \) assign \( D_{\text{minmax}} = D_{\text{max}} \), \( h^* = h \), \( N^* = N \), \( Q^* = Q \).

4. Illustrative Example

Consider a situation when nine different types of elements are available in the market.
Table 1 contains values \( G(h) \) and \( C(h) \) that represent three possible types of relationship between element performance and its cost \( C(G) \): convex, linear and concave (see Fig. 1 for \( C \) and \( G \) presented in Table 1). The elements' costs are normalized such that
\[
\sum_{h=1}^{9} C(h) = 100.
\]

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Figure 1: Cost and Performance of Different Types of Elements

Figures 2-8 show \( D_{\text{minmax}}, h^*, N^*, Q^* \) as functions of various parameters. All the figures show that, when the normalization condition (5) holds, the defender prefers the convex relationship between element performance and its cost. The reason seen from Fig. 1 is that the low performance elements are very inexpensive. Consequently the defender can afford purchasing many elements with low performance. As it was shown in [28], the expected damage proportional to the unsupplied demand is lower in a system consisting of \( N \) elements with performance \( G \) each than in a system consisting of one element with performance \( NG \). For the convex relationship \( C(G) \), \( N \) elements with performance \( G \) each cost less than one element with performance \( NG \), which makes the choice of small elements even more beneficial. For the concave \( C(G) \) this is not the case and the defender has to compromise between risk and cost.

Figure 2 shows \( D_{\text{minmax}}, h^*, N^*, Q^* \) as functions of the contest intensity \( m \) for three different \( C(G) \) curves (linear, concave, convex), when \( F=7, H=9, \varepsilon=1000; r=50, R=25, A/a=1 \). Increasing contest intensity \( m \) makes the per-element protection efforts superiority more critical causing the defender to decrease the number of deployed elements \( N \) in \( m \).
When $C(G)$ is concave, Fig. 2 shows that the defender deploys few elements $N^*$ with high performance $G$ expressed with high $h^*=8$. In accordance with Fig. 1, a substantial cost is needed to obtain low performance, while a moderate cost increase gives substantially higher performance. Conversely, when $C(G)$ is convex, the defender deploys many elements $N^*$ with low performance $G$ expressed with low $h^*=2$ increasing slowly in $m$. The defender accepts increasing the cost to a certain point yielding reasonable performance, but refrains from substantial cost increase yielding only marginal performance improvement. When $C(G)$ is linear, the defender cannot exploit the two opposite advantages of the concave and convex $C(G)$. It tends to choose an all or nothing approach shown with $h^*=1$ versus $h^*=8$ in Fig. 2. This gives high damage $D_{\text{minmax}}$ for most values of $m$ (except when $m$ is very small).

Figure 2 shows that the expected damage $D_{\text{minmax}}$ can depend on the contest intensity $m$ non-monotonically. In many practical situations the values of the contest intensities cannot be exactly determined. Therefore, it would be useful to suggest a practical way to determine the optimal defense strategy for certain intervals of the contest intensity $m$.

The most conservative defense strategy is to assume that the actual value of $m$ (belonging to an exogenously defined interval) is the most favorable for the attacker. This approach is equivalent to assuming that the attacker can choose $m$ within the given interval as a free strategic variable. The minmax defense strategy, thus, minimizes the maximal expected damage $D$ associated with a combination of the most unfavorable circumstances (contest intensity $m$) and the most harmful attacker’s choice of $Q$.

Let $Q^*(N,h,m)$ be the value of the attacker’s effort distribution parameter that maximizes the expected damage $D$ for the given $N$, $h$, and $m$. The defender’s strategy is to choose the number $N$ and type $h$ of elements that minimizes the expected damage $D$ in the range $m_{\text{min}} \leq m \leq m_{\text{max}}$ assuming that the attacker always chooses its best response $Q^*(N,h,m)$:

$$\max_{m_{\text{min}} \leq m \leq m_{\text{max}}} D[N^*,h^*,Q^*(N^*,h^*,m),m] \leq \max_{m_{\text{min}} \leq m \leq m_{\text{max}}} D[N,h,Q^*(N,h,m),m]$$

(6)

for any $(N,h) \neq (N^*,h^*)$.

In order to solve the minmax game of (6) for a given range of contest intensities, the minmax procedure should be modified as follows:

1. Assign $D_{\text{minmax}}=\infty$;
2. for each $h=1,\ldots,H$
   2.1. for each $N=[F/G(h),\ldots,G/C(h)]$
      2.1.1. assign $D_{\text{max}}=0$
      2.1.2. for each $Q=1,\ldots,N$
         find $m^* \ (m_{\text{min}} \leq m^* \leq m_{\text{max}})$ that maximizes $D(h,N,Q,m)$ defined in (4)
         if $D_{\text{max}} < D(h,N,Q,m^*)$ assign $D_{\text{max}}=D(h,N,Q,m^*)$;
   2.1.3. if $D_{\text{max}} < D_{\text{minmax}}$ assign $D_{\text{minmax}} = D_{\text{max}}, h^*=h, N^*=N, Q^*=Q$. 


Figure 2: $D_{\text{minmax}}, h^*, N^*, Q^*$ as functions of $m$ for three different $C(G)$ relations ($F=7, \varepsilon=1000; r=50, R=25, A/a=1$).

Figure 3 shows $D_{\text{minmax}}, h^*, N^*, Q^*$ as functions of defenders resource $r$ for three different $C(G)$ relations when $25m\leq4$, $F=7$, $\varepsilon=1000$, $R=25$, $A/a=1$. The damage $D_{\text{minmax}}$ decreases in the defender’s resource $r$. Again $N^*$ is low and $h^*$ is high when $C(G)$ is concave, and conversely when $C(G)$ is convex. In the concave case $N^*$ increases in $r$. For the linear case, again the defender vacillates between low $h^*$ (with high $N^*$) and high $h^*$ (with low $N^*$). The fluctuations of $N^*$ and $h^*$ are caused by the fact that different combinations of $N$ and $h$ produce very close values of $D_{\text{minmax}}$. When $r$ is low, the attacker attacks all elements, $Q^*=N^*$. As the defender becomes more resourceful so that $r$ increases, the attacker attacks a subset of the elements in the convex and linear cases where $N^*$ is not small, but attacks all elements in the concave case where $N^*$ is small. The defender prefers the linear case over the concave case when $r$ is small or intermediate, and vice versa when $r$ is large.

Figure 4 shows the situation of Figure 3 when $0.2\leq m\leq1$, which gives more egalitarian contests where efforts matter less. $N^*$ in Fig. 4 is always larger than $N^*$ in Fig. 3, and $h^*$ in Fig. 4 is always smaller than $h^*$ in Fig. 3, which reflects the fact that the defender concentrates more efforts on protection of fewer elements with greater performance when the contest is highly intensive (larger $m$). $D$ in Fig. 4 is always smaller than $D$ in Fig. 3 for all types of $C(G)$ relationship when $r$ is small and moderate, but $D$ in Fig. 4 becomes greater than $D$ in Fig. 3 when $r$ is large enough. Indeed the defender always benefits from increase of $m$ when it is superior in resources. In Fig. 4, $Q^*=N^*$ for all $r$ since in more egalitarian contests efforts matter less, and the attacker may as well attack all elements.
Figure 3: $D_{\text{minmax}}, h^*, N^*, Q^*$ as functions of $r$ for three different $C(G)$ relations when $2 \leq m \leq 4$, $F=7$, $\varepsilon=1000$, $R=25$, $A/a=1$

Figure 4: $D_{\text{minmax}}, h^*, N^*, Q^*$ as functions of $r$ for three different $C(G)$ relations when $0.2 \leq m \leq 1$, $F=7$, $\varepsilon=1000$, $R=25$, $A/a=1$
Figures 5 and 6 show $D_{\text{minmax}}$, $h^*$, $N^*$, $Q^*$ as functions of $F$ for three different $C(G)$ relations when $\varepsilon=1000$, $r=50$, $R=25$, $A/a=1$. $D_{\text{minmax}}$ increases in the demand $F$ for $2 \leq m \leq 4$, and $0.2 \leq m \leq 1$ respectively. For the concave case the defender still chooses low $N^*$, but for low demand there is little need for the defender to choose large $h^*$ as in Figs. 2-4, so $h^*$ initially increases in $F$, and thereafter decreases and increases. As the demand increases the defender must increase the cumulated performance of deployed elements. In the concave case it does so by increasing $h$ (choosing elements with greater performance) as this is cheaper than to increase the number of elements. With increase of $h$ the defender even can slightly reduce the number of elements. In the linear and convex cases the defender first increases the system performance by increasing $N$ (deploying more elements with low performance) as this is cheaper than to choose more powerful, but more expensive elements. As $F$ increases further the defender cannot continue to increase $N$ because this causes dissipation of its protection resources among many elements and leads to reduction of the per-element protection effort. Therefore the defender must choose more expensive elements, which reduces the number of elements. This effect is mitigated when the contest intensity is low (Fig. 6).

Figures 7 and 8 show $D_{\text{minmax}}$, $h^*$, $N^*$, $Q^*$ as functions of $R$ for three different $C(G)$ relations when $2 \leq m \leq 4$, $\varepsilon=1000$, $r=50$, $F=7$, $A/a=1$ for $2 \leq m \leq 4$ and $0.2 \leq m \leq 1$ respectively. As is evident from the figures, $D_{\text{minmax}}$ increases in the attacker’s resource $R$. For the concave case $N^*$ is small and decreasing in $R$, and the defender chooses powerful elements ($h^*=8$). The attacker prefers the concave case when $R$ is above a minimum, and chooses $Q^*=N^*$. For the convex case $N^*$ has an overall inverse U shape. The reason is that when $R$ is small, the defender faces a weak opponent and there is no need to deploy many elements.
The defender deploys few elements with intermediate performance, and succeeds in the highly intensive contests. As $R$ increases, the defender deploys more elements, with lower performance. As $R$ increases further, the high contest intensity $2 \leq m \leq 4$, which is costly, induces the defender to deploy fewer elements to ensure effort superiority and avoid too much effort inferiority compared with the attacker. Concomitantly, the defender chooses higher $h^*$ (higher performance $G$) for these elements. This effect is mitigated when the contest intensity is low (Figure 8).

4. Conclusion

A system of identical parallel elements is purchased and deployed. The cumulative performance of the elements must meet a demand. There are different types of elements characterized by their performance and cost in the market. We consider convex, linear, and concave relationships between performance and cost. The defender determines the system structure by choosing the type and the number of elements in the system and distributes its limited resource between purchasing the elements and protecting them from outside attacks. The attacker chooses the number of elements to attack and distributes its limited resource evenly among all the attacked elements. The vulnerability of each element is determined by a contest success function between the attacker and the defender. The damage caused by the attack is associated with the cost of destroyed elements and the reduction of the cumulative system performance below the demand. The defender minimizes the damage anticipating the best attacker's strategy for any system structure. It is shown that the variables that determine the optimal system structure can depend non-monotonically on the contest intensity parameter, which is commonly uncertain. An algorithm for determining the optimal system structure under uncertain contest intensity is suggested, which is based on the worst case approach. Illustrative numerical examples demonstrate optimal system structures that cannot be determined based on intuition.
Figure 7: $D_{\text{minmax}}, h^*, N^*, Q^*$ as functions of $R$ for three different $C(G)$ relations when $2 \leq m \leq 4$, $\varepsilon=1000$, $r=50$, $F=7$, $A/a=1$.

Figure 8: $D_{\text{minmax}}, h^*, N^*, Q^*$ as functions of $R$ for three different $C(G)$ curves when $0.2 \leq m \leq 1$, $\varepsilon=1000$, $r=50$, $F=7$, $A/a=1$.
The examples show that the optimal number of elements can depend non-monotonically on the amount of actors' resources and on the system demand. In some cases the expected damage is similar for different combinations of number and type of deployed elements, which causes fluctuations in these variables. The fluctuations disappear when the contest is not intensive because in this case achieving the effort superiority becomes less important. Low contest intensity induces the attacker to attack all elements, whereas high contest intensity induces the attacker to attack a subset of the elements in order to achieve the effort superiority in attacked elements. For the linear relationship large fluctuations occur between the number of deployed elements and the performance of these since the expected damage is similar for different combinations of deployed elements and the performance of these.

References


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