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Studying flexibility in modularisable vehicle systems

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Abstract

Some systems continue working under partial failure; errors can be made in assessing the performance of such systems if static measures are used. Systems that appear to be equal on the basis of idealised data can perform differently under component loss. For some system features, such as component modularity, the evidence of benefits, based on static measures, is equivocal. We propose that a modular design will perform better than a nonmodular design under component loss. We consider two systems, each designed to a particular budget and completely effective over all variations contained in the design context. One of the systems has modular components. We use the mission criticality model to assess the benefits of introducing this component modularity and compare the results with a related static assessment. When demands are variable, the modular system is superior under component loss, due to its greater component redundancy.

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1 Introduction

Many systems, including military logistics systems, must continue to provide timely services even when many components are disabled. Initial component redundancies enable the maintenance of system services under component loss until redundancies are exhausted, and a combination of redundancy and adaptation has been proposed as the key to reliable or dependable systems [3], but when a system is being purchased initial redundancies will always be restricted by budgets. When the system takes the form of a fleet of vehicles and performance is measured under component loss, we believe that a modularised fleet will be able to provide better performance than a fleet of fixed trucks.

Modularisation, in the form of containerisation and the use of trailers, has been highly successful in commercial transportation, essentially because it enables vehicles to be used more efficiently, that is it lowers costs. With a fixed truck, the motor and transmission must lay idle while the truck is being loaded or unloaded, whereas a container can be loaded without a motor being present and quickly attached to a flatbed or truck chassis when it is packed. Modularisation might also provide advantages, in both cost and performance, for military logistics systems. While it is obvious that similar cost advantages will apply, there is little hard evidence to support expectations of performance advantages. The effect of modularisation on vehicle number and mix has been studied for some scenario parameters including network topology, task concurrency and time criticality [2]. We concentrate on performance advantages and propose that the lack of evidence is the result of confounding factors, including inadequacies in the measures used to predict performance, possibly indicating the need for a theoretical basis. We demonstrate that there are significant performance differences between fixed and modular fleets when an appropriate measure is used. We also reveal the source of these differences.

We seek to define the performance change that is due to modularisation, so we eliminate or control other factors that will influence performance. These include differences in resourcing, biased choice of test scenarios, uncontrolled interactions between components, differences in survivability between the two fleets, and errors in the measures used for comparison. Resourcing differences are difficult because the two systems may be inherently different and may have quite different costs. We take the view that the budget is the overriding factor and look at the performance expected from two different systems crafted from the same budget. Constraining the overall budget also simplifies the optimisation problem that underlies the performance comparisons. Bias in scenarios cannot be completely eliminated. We minimise it by setting up scenarios that bring out the differences between the options and show the conditions under which particular options are to be preferred. Our two test systems have inherent differences in flexibility of attachment between motive units and load carriers, so we eliminate other forms of flexibility from the tests by removing interactions between different types of load carriers. Elimination of differences in survivability is a little more difficult and we have chosen to equalise the survival probabilities for each component type and assume that component types survive independently. This is computationally simple and almost eliminates the differences in system survival. It also discriminates marginally against the modular fleet, so that there is no question over the validity of any advantages that are found for that fleet. Errors in measures are eliminated by the use of a consistent measurement framework. With the exception of measurement errors, all of the factors will be uncontrolled in reality so we will also need to understand the interaction of modularisation with these factors. However, in this article we concentrate on the intrinsic contribution of modularisation to fleet performance.

The measurement framework [1] capitalises on interdependencies between measures and is a generalisation of the performability model [4]. For logistics systems, the measures of effectiveness and survivability have been shown to be dependent and it is an error to assume independence. The framework produces an expected value of system performance under component loss and under differences in scenario. We choose effectiveness as the performance measure and calculate the expected value under component loss applying the approach to a realistic fleet design problem: the choice between modular and non-modular fleets. We explore the difference in calculated effectiveness when the interaction of effectiveness and survivability is taken into account and when it is not.

2 Basic equations

The basic equations fall into two types: those that define the budget limited test case, and those that define the measure of system effectiveness that will be used to discriminate between the fleet options.

2.1 Test case

The test problem involves two different commodities that cannot be carried with the same equipment. This is common, for example petrol tankers and water tankers cannot be used interchangeably, and two different types of load carrier are required. In a fleet of fixed trucks, two different types of truck are required. We represent the fleet of fixed trucks by the pair (X_1, X_2) where X_i is the number of trucks of type i. Similarly, a modular fleet is represented by (Y, Y_1, Y_2) where a module of type i carries the same type of commodity as a truck of type i, and where Y is the number of motive units, or truck chassis. Each truck type has the same price in our test case, so the total cost for a fleet of fixed trucks is $X_1 + X_2$, effectively normalising the price to 1. If the cost of each module is β and the cost of each motive unit is α, then a choice of numbers of modules (Y_1, Y_2) means that the number of motive units, limited by budget, is

$$Y \leq \frac{X_1 + X_2 - \beta(Y_1 + Y_2)}{\alpha}\,, \tag{1}$$

where Y, Y_i, X_i all have nonnegative integer values. We assume that the cost of a module plus a motive unit will be greater than or equal to the cost of a fixed truck, because of the extra cost of allowing a module to be attachable to the motive unit. When $\alpha + \beta > 1$ there will be a cost premium $\gamma = \alpha + \beta - 1 > 0$ on the modular fleet. The objective is to determine and explain the differences in system effectiveness between the two fleets.

2.2 Performance under component loss

The framework [1] allows the expected value of system effectiveness to be calculated under component loss and over the range of demand probabilities that are expected over a range of scenarios. In this exploratory work we apply the approach to a single scenario at a time, so we just calculate the expected value under component loss.

If the probability of a component surviving through the tour of duty is p, then the probability of k out of n surviving is the binomial factor $B(n,k,p)$. In each possible system state, for example (k_1,k_2) for the fixed fleet or (j,j_1,j_2) for the modular fleet, the system will have an effectiveness measure, either $\omega_{k_1k_2}$ or $\omega_{jj_1j_2}$, calculated from the relevant time series. This effectiveness ω for a system in a particular state is called *mission criticality* [1] and is constrained by $0 \le \omega \le 1$. In the case of the fleet of fixed trucks the expected value of system effectiveness is

$$E(X_1,X_2) = \sum_{k_1=0}^{X_1}\sum_{k_2=0}^{X_2} B(X_1,k_1,p)B(X_2,k_2,p)\omega_{k_1k_2}\,, \qquad (2)$$

whereas the expected effectiveness for the modular fleet is

$$E(Y,Y_1,Y_2) = \sum_{j=0}^{Y}\sum_{j_1=0}^{Y_1}\sum_{j_2=0}^{Y_2} B(Y,j,p)B(Y_1,j_1,p)B(Y_2,j_2,p)\omega_{jj_1j_2}\,. \qquad (3)$$

We assume, in equation (3), that losses of motive units and modules are independent of each other. If any essential part of a fixed vehicle is disabled, the whole vehicle is disabled, whereas a motive unit may be disabled while the module is still usable, and vice versa. The exact dependence between destruction of motive unit and destruction of module is very difficult to estimate and is likely to be fuzzy. We compromise by assuming independence and then taking the worst case for the modular design: where the probabilities for disablement of modules and motive units are equivalent to the scrapping of usable units if the companion units are disabled.

3 Method

Within a scenario the number pairs representing the fixed fleets that are fully effective if all of the components are available for use will form a semi-bounded infinite set. If a fleet is fully effective, then another fleet with one or more extra components will also be fully effective, but there will be one number pair that minimises the number of components of each type: if fewer components are used, the fleet will not be fully effective. This is the minimal effective fleet and the extra components in the other effective fleets are said to be redundant. Calculation of the expected value of system effectiveness under component loss (equation (2)) gives a different view of the performance of each of the possible fixed fleets. Each effective fixed fleet defines a budget and equation (1) enables the choice of a set of modular fleets, each of which will have a system effectiveness under component loss. At each level of redundancy in the fixed fleet there will be some ways to distribute the redundant vehicles between component types and each different way will also have a system effectiveness. We compare the maximum system effectiveness for each fleet type at each level of redundancy, within each scenario.

3.1 Scenarios

In general, scenarios are difficult and expensive to construct because they represent possible futures that may need to be dealt with. They have to be populated with several layers of information before the tactical situation is defined. For logistics, the end product of this process is a time series of expected demands. These demands need to be mapped, through a process of scheduling, loading, binning and routing, to a time series of scheduled tasks. The time series are influenced by many factors that are irrelevant to the current test. Therefore we short circuit the scenario development process and represent scenarios directly by time series of scheduled tasks. In the remainder of this article we use the terms *tasks* and *demands* interchangeably, noting that a process of scheduling et cetera has been performed. We assume that the task time series do not depend on the characteristics of the two fleet systems and thus that fixed and modular fleets face identical time series. A modular fleet differs from a fleet of fixed trucks in that it has extra inbuilt flexibility, so we expect it to be better suited to time series where demands are varying. We thus construct two basic scenarios: one with constant demands and one in which demands for different types of truck/module alternate. We also include a time period of peak demand in which a large number of trucks or modules need to be used.

For Scenario 1 the demand for vehicles is constant over all time periods, with five type 1 vehicles and six type 2 vehicles being required in order to be completely effective. If a fleet state contains fewer than five type 1 or six type 2 vehicles, the effectiveness is reduced proportionally. Effectiveness also needs to account for priority, with type 1 loads having a higher priority of value 2 than type 2 loads (priority 1). This definition of priority is against the normal convention. In this analysis, the term priority describes a weight that is used to represent the importance of a task. When $\gamma > 0$, the modular fleet starts with an asset deficit compared with the fixed fleet. When demand is variable, there is opportunity for the modular fleet to use its flexibility to counteract its asset deficit. Thus we hypothesize that Scenario 1 will favour the fixed fleet when $\gamma > 0$ and will be neutral when $\gamma = 0$.

In Scenario 2, only type 1 vehicles are required at time period one and only type 2 vehicles are required at time period two. This pattern is repeated for all subsequent pairs of time periods. In odd time periods, five type 1 vehicles are required for full effectiveness. In even time periods, six vehicles of type 2 are required. As for Scenario 1, type 1 loads have priority 2 and type 2 loads have priority 1, and for smaller numbers of vehicles effectiveness is reduced proportionally. We expect this scenario to favour the modular fleet.

In each scenario the mission criticality for the fixed fleet has the form of a piecewise linear function of each of the component types independently. For the minimal effective fixed fleet, where $(X_1, X_2) = (5, 6)$, the mission criticalities for both scenarios are governed by two independent linear reductions from 1 to 0 under component losses and it can be seen, by following through the algebra, that the proportional reduction of system effectiveness with the loss of each component leads to the expected value for system effectiveness of the minimal fixed fleet being equal to the value of probability of survival for a single component.

3.2 Fleet design

In this test, fleets are defined separately for each scenario. The components X_i of the fleet of fixed trucks are set equal to the maximum demand for type i vehicles over all time periods in the scenario. The numbers of vehicles may be increased by adding extra, or redundant, vehicles of each type. Once the numbers of fixed trucks are set, the budget becomes X_1+X_2 and all combinations of (Y, Y_1, Y_2) that satisfy equation (1) are possible designs for the modular fleet. For example, the modular fleet might initially be defined via $Y_i = X_i$, with Y being calculated via equation (1), but there is freedom to redistribute the budget, either by increasing the numbers of modules and reducing the number of motive units, or vice versa, in order to achieve maximum performance under component loss. In equation (1), α and β are control parameters and Y, Y_1 and Y_2 are variables. On the basis of static measures, which are based on the assumption that each fleet remains in its design state, both fleets are completely effective except in Scenario 1 where the modular fleet is less effective due to reduction in component numbers via the cost premium. There is no reason to believe that component survivability will be different in the two fleets, so the probability of a component being disabled during the tour of duty is taken to be the same for each component type and component types are taken to be damaged independently. This tends to marginally reduce the system performance of the modular fleet.

The values of Y, Y_1 and Y_2 are reduced as components are disabled. When the values are the original design values, the fleet is said to be in its design state.

3.3 Optimisation in scenario based trials

For a given level of redundancy in the fixed fleet, the extra vehicles may be distributed in different ways between the two truck types, and each possible distribution will have a different value of system effectiveness in a scenario.

The performance of the fixed fleet at that level of total redundancy is represented by the distribution of vehicles that maximises the system effectiveness.

Adding redundancies to the fleet of fixed trucks increases the budget and increases the number of modules and motive units that can be bought. The extra modules can be distributed in different ways between the two module types and we can also choose to swap motive units for modules and vice versa. Thus the modular system has an extra degree of freedom in distributing components.

4 Results

Results depend on the values of β and γ, the component survival probability p_s and the level of redundancy in the fixed fleet. The two scenarios are identical from the point of view of the fixed fleet and the system effectiveness for the fixed fleet increases with increase in the component survival probability p_s. Table 1 shows the performance of each fleet depends on the number of redundant vehicles in the fixed fleet. The overall trend is for the difference in system effectiveness between the fixed and modular fleets to be reduced as the inbuilt component redundancy increases. The results are for a component survival probability $p_s = 0.8$.

In Scenario 1, performances are nearly equal for the two fleet options when there is a zero cost premium for the modular fleet (Table 2), but for higher cost premiums the budget limited modular fleet has a reduced performance (for example, 0.7 versus 0.8 when premium is 0.15). Note that the mission criticalities used to generate these estimates of system effectiveness deliberately excluded the effect of load and unload times, these having been covered in a separate study [2]. The importance of loading times will vary with context. In some cases they will be unimportant, and, where they are important, the size of the effect will vary with context. This effect will only be felt by the fixed fleet and, since it always reduces system effectiveness

Table 1: Maximum system effectiveness, at each level of total redundancy in the fixed fleet, for fixed and modular fleets when $\beta = 0.3$ and $\gamma = 0$.

	Redundancy	Fixed	Modular	Difference
Scenario 1	0	0.80	0.79	-0.01
	1	0.87	0.84	-0.03
	2	0.91	0.89	-0.02
	3	0.94	0.93	-0.01
Scenario 2	0	0.80	0.96	0.16
	1	0.87	0.98	0.11
	2	0.91	0.99	0.08
	3	0.94	1.00	0.06

Table 2: Effect of cost premium on modular fleets when $\beta = 0.3$ and there are no redundant vehicles in the associated fixed fleet.

γ	Scenario 1	Scenario 2
0.00	0.79	0.96
0.05	0.76	0.95
0.10	0.73	0.94
0.15	0.70	0.92

of the fixed fleet, it could remove any superiority of the fixed fleet even in Scenario 1.

For the fixed fleet, the total redundancy is simply the difference in the total number of components $X_1 + X_2$ between the current fleet and the minimal effective fleet. Total redundancy for the modular fleet is more difficult to characterise, so we use the total redundancy of the associated fixed fleet. In Scenario 2, the performance of the modular fleet, for zero redundancy in the fixed fleet, varies from 0.96 to 0.92 as the cost premium rises from zero to 0.15.

Addition of redundant vehicles to the fixed fleet improves its performance. At $(5, 6)$ the system effectiveness is 0.80, at $(6, 6)$ system effectiveness is 0.87 ($(5, 7)$ giving 0.83 by comparison), $(7, 6)$ has a system effectiveness of 0.91 and $(7, 7)$ gives 0.94. Modular fleets based on the same budget have system effectiveness values of 0.96 $(8, 8, 9)$, 0.98 $(9, 9, 9)$, 0.99 $(10, 9, 10)$ and 1.0 $(11, 10, 10)$. Thus, with sufficient redundancy, the fixed fleet approaches the performance of the modular fleet. The difference is in performance per unit cost.

The effect of a cost premium on the possible performance of a modular fleet can be seen in Table 2. System effectiveness is reported for fleets based on a budget with no redundancy in the fixed fleet. Modular fleet compositions in Scenario 2 are $(8, 8, 9)$ (0.96), $(8, 8, 8)$ (0.95), $(8, 7, 8)$ (0.94), and $(8, 7, 7)$ (0.92).

As expected, component redundancy is a significant factor in the value of system effectiveness. This is true for both fixed and modular fleets but modular fleets are not limited to swapping between types of modules and can swap motive units for modules to obtain the most effective balance. For example, in Scenario 2 a fixed fleet of (5,6), or eleven trucks, has a system effectiveness of 0.8 while the modular effectiveness of 0.96 was achieved by sacrificing three motive units and buying extra modules. Redundancies can also be swapped in the fixed fleet, but the modular fleet gives an extra degree of freedom. Note that this choice on the allocation of redundancies is made at the design stage. In this test case we make the choice on the basis of a known scenario.

Calculation of system effectiveness based on priority allows a balance to be achieved between performance on resource hungry tasks and maintenance of performance under significant loss of components as long as either the fleet option or the budget has sufficient flexibility.

5 Discussion

Under the conditions of this test case we demonstrated a clear advantage for a modular fleet over a fleet of fixed trucks in Scenario 2, which involved some variation in the demand. This was achieved by the use of a performance measure that accounted for the effects of component losses, whereas the fixed and modular fleets were equally effective in their design states. Now we discuss the apparent reason for the advantage, the effect of variations in scenario demands, the possible effect of factors that were excluded from the test case, the limitations that might be produced by extra costs associated with modularisation and the reduction in the performance gap between the two fleet types that would result from an increase in the probability of component survival.

In Scenario 2, where the demand for commodity types alternated, the modular fleet was superior, for all levels of redundancy in the fixed fleet, because it had an extra degree of freedom in the allocation of budget to purchasing the different types of components. This was driven by the creation of an extra redundancy, with the number of motive units that were needed, for full effectiveness, being less than $X_1 + X_2$. This change alone brought an improvement in the system effectiveness under component loss; however, the improvement was able to be maximised by sacrificing some of the redundant motive units to purchase extra modules. However, this advantage will not occur simply because a scenario has variation in demands with respect to time. If demands for the two commodities over time were highly correlated, and particularly if the peak demands occurred at the same time, no redundancy would be created by modularisation. The major benefit from modularisation occurs when the peak demand for motive units is much less than $X_1 + X_2$. This situation creates a large redundancy in the number of motive units which enables the transfer of redundancy to modules in order to maximise system effectiveness.

Modularisation introduces a form of flexibility in that motive units can be separated from modules, and we have estimated the benefit of introducing this flexibility without the confounding effects of other forms of flexibility. In normal situations, other forms of flexibility will be present. For example, vehicles might be multi-purpose. If the other flexibilities are present in both fleet types, they will improve the performance of both fleets and will thus reduce the gap between a fixed fleet and a modular fleet in the values of system effectiveness under component loss. Thus we are demonstrating the benefits of functional versatility and showing that modularity is one way to achieve such versatility.

An increase in purchase price for a motive unit plus a module over the price of the equivalent fixed truck can reduce the number of motive units that can be purchased. As this cost premium increases there will be a point where the loss of motive units due to increased cost will exactly counterbalance the possible creation of redundant motive units. At this point the modular fleet will have the same performance under component loss as the fleet of fixed trucks. At higher premiums the modular fleet will be inferior.

We now understand how previous verdicts on modular fleets could be equivocal. There is a substantial difference between the expected value of system effectiveness under component loss and the effectiveness calculated under design conditions. Any advantages held by the modular fleet are demonstrated by a superior value of system effectiveness yet the size of the gap has a strong dependence on the probability of survival for each component. The results we discussed have been for the case where each component has a probability of surviving the deployment of $p_s = 0.8$, which represents an intensive conflict. If the probability of survival is greater, say $p_s = 0.95$, the gap between the performances of the two fleets is substantially reduced. The survival probability can also be increased by increasing the capability of individual components to cope with dangers.

We tried to equalise the investment costs, for the two types of fleet designs, by equalising the budgets. However, this does not equalise whole of life costs. For example, reducing the number of motive units will cause each unit to be used more heavily, causing the units to be replaced at an earlier time. This earlier replacement represents an extra investment cost. Our budget is a surrogate which we used because of the enormous difficulty involved in the evaluation of the benefits of functional versatility.

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