Journal of Defense Modeling and Simulation: Applications, Methodology, Technology
1–17

DOI: 10.1177/1548512916651939
dms.sagepub.com
SAGE

An integrated design approach for evaluating the effectiveness and cost of a fleet

Kiran D'Souza[1], Alparslan Emrah Bayrak[2], Namwoo Kang[2], Hui Wang[3], Berk Altin[2], Kira Barton[2], Jack Hu[2], Panos Papalambros[2], Bogdan I Epureanu[2], and Richard Gerth[4]

Abstract

This work presents a new method for designing and evaluating different fleet paradigms to determine an effective and cost efficient solution. The method requires the user to define a set of functions which must be carried out by the fleet, as well as a set of candidate vehicles or systems that can carry out these functions. These function and fleet models are then evaluated to determine their performance. All the data is then fed into a stochastic dynamic fleet operation model to identify the amount of vehicles or systems needed to complete each mission defined on a fixed time horizon. The output of the fleet operation model is then used by cost models to determine the cost of completing each fleet mission. The overall approach is demonstrated on a military fleet composed of two different types of vehicle: a conventional fleet and a fleet composed of modules. The method shows the potential for savings using a modular fleet for a hypothetical fleet mission profile; more work in this area is suggested.

Keywords

Modularity, fleet optimization, system design, fleet operation simulation

1. Introduction

The military is interested in understanding the relative benefits of a modular vehicle fleet versus a traditional vehicle fleet. This paper outlines a simulation framework that was created to be able to address this question. The framework will be described and then demonstrated based on a hypothetical fleet mission profile. The results presented here are meant to be illustrative of the type of analysis that can be performed within the framework. The results are not meant to be accurate or make a definitive statement as to the advantages and disadvantages of modularity.

Developing and designing a fleet of vehicles to accomplish a particular goal is a complex task. Whether this fleet is a city-based public transportation system, a fleet used for distribution and delivery of goods to a large customer base across the country, or a military fleet in a hostile environment, it is a challenge to define and evaluate the utility and the cost of procuring and maintaining the fleet.

A great deal of research has been done on optimizing transportation fleets. For example, in the freight transportation field,[1] the emphasis has been on service network design problems (SNDP).[2] The SNDP addresses the most efficient way to move commodities through a network by determining the optimal set of vehicles, routes, and schedules. Similar work has also been done in the airline industry to optimize the routing, flight selection, timing and fleet selection.[3] Analysis of airfleets has also been carried

[1]The Ohio State University, USA
[2]University of Michigan, USA
[3]Florida State University, USA
[4]US Army, TARDEC, USA

Corresponding author:
Kiran D'Souza, The Ohio State University Mechanical and Aerospace Engineering Department, 2300 West Case Road, Columbus, OH 43235.
Email: dsouza.60@osu.edu

out for improving airmail distribution.[4] Given a deterministic demand of goods, optimizing the route of inventory flows through postal distribution centers has also been studied.[5] The focus of this type of fleet design research has been on optimizing the network for distribution of commodities (i.e. goods, mail, people), and not on designing and analyzing the fleets themselves for completing their tasks. The fleets were given and the network was altered. The effectiveness of the fleet was not analyzed, but rather the effectiveness of the networks.

This work differs from previous research in that it does not assume a fixed fleet (the vehicle mix is a variable), and it evaluates overall fleet performance based on the resources needed to complete a set of functions that are called in a stochastic manner. It is a vehicle fleet design and evaluation problem, not a network optimization problem. Recent work done by Ceder[6] addressed aspects of the fleet design problem. Ceder applied simulation modeling to evaluate the effect of integrating a smart shuttle transit service within a rapid transit system on traffic congestion. The approach focused on designing the fleet to handle the complicated logistics and did not consider total costs.

One important aspect of this framework is it integrates a fleet's performance metric (e.g., the ability to handle a set of tasks over time) with its complete life cycle cost (acquisition, operational, and retirement costs).[7] A review of recent trends in freight transportation research[8] showed cost analysis to focus on fleet operation (the cost of moving freight when one already has a fleet) and exclude acquisition cost. Similar research in the naval shipping industry only emphasizes optimizing fleet energy efficiency subject to certain delivery time constraints, again neglecting acquisition costs.[9] The research that does address life cycle costs is focused on understanding or justifying the life cycle costs of specific vehicle types, such as hybrid electric vehicles,[10] naval ships,[11], or planes,[12] as opposed to full fleets of disparate vehicles.

Brunson et al.,[13] Shrake et al.,[14] and Fu and Ishkhanov[15] looked at parts of the problem considered here, namely doing an overall analysis of the life cycle cost and performance of an entire fleet. Brunson et al. focused on a very specific application of a small fleet of three vehicles where they compared three options: refurbishment, replacement or upgrading. The work is not broadly generalizable to be used for a wide variety of fleets or systems. By contrast, this work highlights a specific case study comparing a conventional and modular fleet, but also lays out the groundwork for the development of functions and the creation of the stochastic dynamic model to evaluate a variety of systems in a new manner while accounting for stochasticity in function calls, maintenance, damage, etc. Shrake et al. looked at a life cycle comparison of diesel and biodiesel vehicles. Again the variety of vehicles was small, and the cost was restricted to only operational cost (maintenance, repair and fuel). Fu and Ishkhanov conducted a study on how to design a fleet of the right size and mix. The scope of the fleet was larger than the other works, but its focus was more on fleet performance, i.e., completing the functions. It did not factor in the cost, which was left for future work.

In this work we introduce a methodology to design, model and evaluate different fleet configurations and fleet paradigms based on fleet effectiveness and life cycle cost. The inputs to the methodology are the types of vehicles that are available for use in the fleet. The methodology determines the number of each vehicle type needed to meet the fleet's mission. The fleet mission is divided into a set of function models. These functions are parameterized tasks that must be completed, such as the delivery of a given payload for a particular distance with a certain terrain-speed profile. These function models are specific to the fleet mission. For example, the vehicle functions for the delivery of packages by the Post Office will be different from those for administering disaster relief after a natural disaster. Each function is evaluated using vehicle specific simulation models to determine the suitability of each vehicle to each function. In addition the simulation models must output vehicle performance data—in this case, fuel consumption and time to function completion. The vehicle types, function models, and function simulation data are integrated into a stochastic dynamic simulator which creates multiple mission scenarios based on the expected stochastic need for particular functions. The stochastic dynamic simulator computes the types and number of vehicles needed (fleet mix) to meet the fleet's mission with a certain confidence level.

Several works from the ''systems of systems'' research have also focused on the design of fleets. The definition of ''systems of systems'' has been defined in a variety of manners, however, the definitions share several attributes, namely bringing together several independent self-contained systems to enable a capability or set of capabilities. Mane et al.[16] looked at existing and yet to be designed aircraft by using an optimization approach to solve the mixed integer nonlinear programming problem for airline resource allocation. Taylor and de Weck[17] used an integrated optimization approach for network, aircraft and operations design for overnight package delivery. Additional works[18,19] address both aircraft sizing and airline allocation for a number of time horizons. Patterson et al.[20] looked at the design of a traditional and modular fleet of unmanned air vehicles from a system of systems perspective where a set of mission profiles are called with a certain probability. Although this was similar in many ways to the study presented in this work the focus of the analysis of Patterson et al. is on the development and analysis of the flexibility of the fleets. In general, the current work relates to past system of systems research but the current work goes beyond enabling a particular capability by also providing comparative metrics between design choices by considering operational coverage and life cycle cost.

Previous work has shown how a vehicle could be designed to meet a probabilistic set of function parameters.[21] This work extends that idea to the design of a fleet to meet a probabilistic set of function calls. The fleet mix is then fed into operating, transportation, and acquisition (considering manufacturing) cost models to estimate the total fleet cost to perform all functions with a given confidence level. Section 2 describes each modeling method in detail. Section 3 presents a case study where the approach is applied to a military fleet designed using two different paradigms: a conventional approach and a modular approach. Section 4 ends with a discussion and conclusions.

2. Design and evaluation of a fleet

In this section we discuss the input needed for the design and evaluation of a fleet as well as each of the models used in this process. First, we describe the vehicle types and the development of functions from known or expected requirements from the fleet. Then, we explain the high fidelity simulation models for vehicles completing functions. After that, we introduce a stochastic fleet operation model which uses the information from the fleet inputs, function models and simulation models to determine the needed fleet mix. Finally, we present the cost models: acquisition (considering manufacturing), transportation, and fleet operating cost.

2.1. Fleet, function and vehicle models

The design of a fleet varies greatly based on its application. At the design stage, the overall mission of the fleet must be broken down into functions that can be completed by vehicles or components of the fleet, e.g., for a public transportation system a function would be to move a given number of people from point A to point B in a certain amount of time. The overall mission of the fleet is to complete all required functions at the required time. These dynamic function demands can be deterministic, stochastic or both depending on the application. Therefore, the functions must be assigned expected probabilities to be called at any given time instant (where a probability of one would mean a deterministic functional demand). Further, there may be interdependencies between functions, e.g., a military combat function might trigger an ambulance function with a certain probability. So, the definition of a fleet function should include its probabilities and triggers. An already designed set of vehicle types can then be evaluated using the models in the following subsections. If, however, one does not have a set of vehicles types, then the decomposition of the requirements of the fleet mission into functions elucidates the types of vehicles or systems needed to complete the functions.

Each vehicle or system type in the fleet must be evaluated against the various functions to determine the amount of resources (e.g., time, fuel, people) each function requires. This is typically done using one or more high fidelity vehicle performance models, such as vehicle dynamics models and other vehicle performance models. Since a function can be completed by multiple vehicles or systems, it is necessary to individually simulate all possible ways a function can be completed using the appropriate models given the function requirements. Once each vehicle type's resource requirements (fuel, time, people) has been determined for every function, the fleet operation simulation, discussed next, selects which vehicle or system should be used by minimizing the required resources.

2.2. Fleet operation model

A stochastic fleet operation model is devised in order to evaluate the fleet performance (see Figure 1).

Stochastic simulations of fleet operation can be used to determine the amount of resources needed to complete all the functions, or it can predict the level of function coverage for a fixed set of resources. The fleet operation model runs in time increments over a specified time horizon (e.g., hourly for one month, monthly for 10 years, etc.). At every time increment over this time horizon it calls the mission functions based on their chosen probabilities (see Section 2.1). This process is then repeated numerous times to statistically determine how well the fleet covers the functions. As mentioned in the previous subsection the simulation can be set up so that functions trigger additional functions (interdependence of functions). At each time step the functions that are being called or triggered must be updated and tracked so that when functions end the resources can be updated and there can be a check for triggered functions. Also, maintenance (e.g., due to wear or conflict) can be modeled as a deterministic or a stochastic process. The parameters for the fleet can be adjusted to obtain 100% function coverage with a given confidence. These parameters can then be used to determine the needed inventory levels for the fleet and the needed rate of resupply due to maintenance or damage to the vehicles.

In the proposed model, the fleet operation simulation is governed by two equations that track the functions $\mathbf{f}(t)$ and resources $\mathbf{r}(t)$ over time t. These equations can be expressed as follows:

$$\begin{aligned} \mathbf{f}(t) &= \mathbf{f}^{\mathrm{CONT}}(t-1) + \mathbf{T}\mathbf{f}^{\mathrm{END}}(t-1) + \mathbf{v} \\ \mathbf{r}(t) &= \mathbf{r}(t-1) - \mathbf{C}[\mathbf{f}(t) - \mathbf{f}(t-1)] + \\ &\mathbf{R}\mathbf{f}^{\mathrm{END}}(t-1) - \mathbf{D}\mathbf{f}^{\mathrm{END}}(t-1) \end{aligned} \tag{1}$$

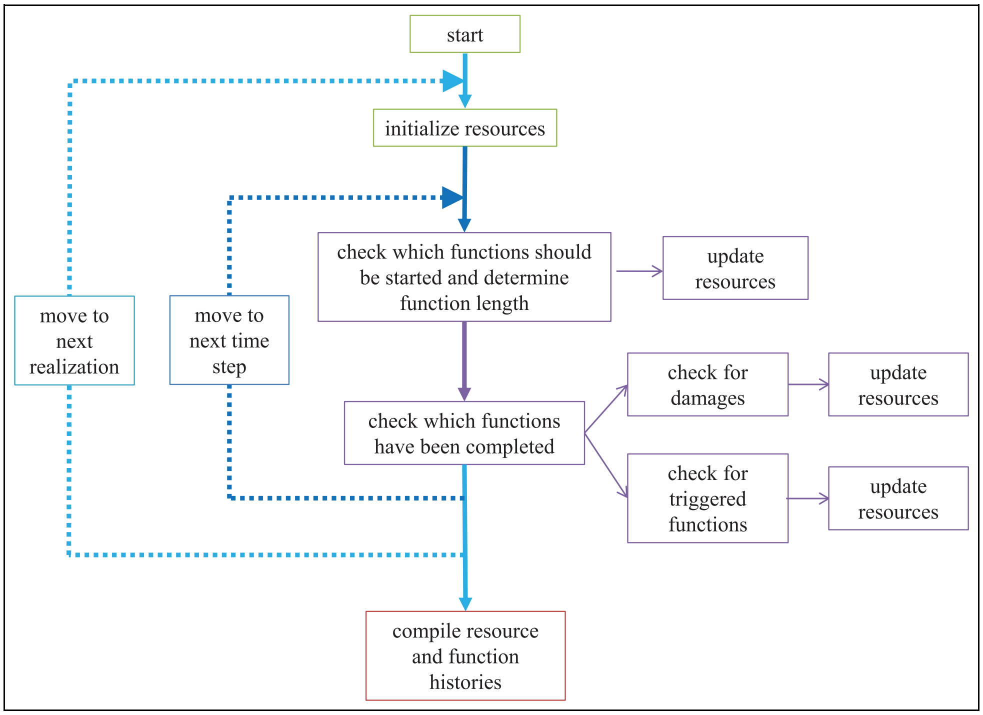

Figure 1. Structure of the fleet operation algorithm.

where $\mathbf{f}^{\mathrm{CONT}}(t-1)$ are the functions that are continuing from time $t-1$ to t, $\mathbf{f}^{END}(t-1)$ are the functions that are ending, $\mathbf{T}$ is a stochastic matrix of triggered functions by completed functions, $\mathbf{v}$ is a stochastic vector of called functions at each time step (can also be partially deterministic for functions called on a specific schedule), $\mathbf{C}$ is a deterministic matrix that accounts for resources being used by functions, $\mathbf{R}$ is a deterministic matrix that adds resources from ending resupply functions, and $\mathbf{D}$ is a stochastic matrix that accounts for damage at the end of functions. The simulation is set to occur over a fixed time horizon, and since it is stochastic, many realizations are simulated to better understand fleet operation.

2.3. Cost models

To properly evaluate the cost of a fleet one must consider its acquisition cost, transportation cost (if a fleet is not stationary but shipped as in the case of disaster relief or military operations), and the fleet operating cost.

Modeling of the acquisition cost varies greatly by the application. If the fleet is being designed from vehicles or systems that are already available, then the acquisition cost for each component or system would be known. If, however, a new design paradigm is being explored then the acquisition cost must be calculated considering the manufacturability of the new designs.

A transportation cost exists and must be modeled for cases where the fleet is being used with the intention of temporarily deploying at various locations and then bringing it back with the expectation of future redeployment. This deployment and redeployment limits the practicality of the types of systems and vehicles that can be considered and adds another dimension to the cost model.

The fleet operating costs are the cost of fuel needed by the fleet, the maintenance and repair costs, and operator costs. Other operating costs can be added depending on application and desired fidelity.

There will be a trade-off between all of these costs, but especially between the acquisition and the operating costs. Autonomous systems may have a higher acquisition cost, but may have a lower overall fleet operating cost, because of the reduced labor required (fewer drivers needed).

3. Case study: conventional & modular military fleets

To demonstrate an application of this new system design and analysis tool, a case study was created that analyzes and compares two military fleets that were developed from two different design paradigms. The first is a fleet composed of vehicles that are produced in a conventional manner. The second is a fleet composed of modules that can be arranged into different vehicles to complete the desired

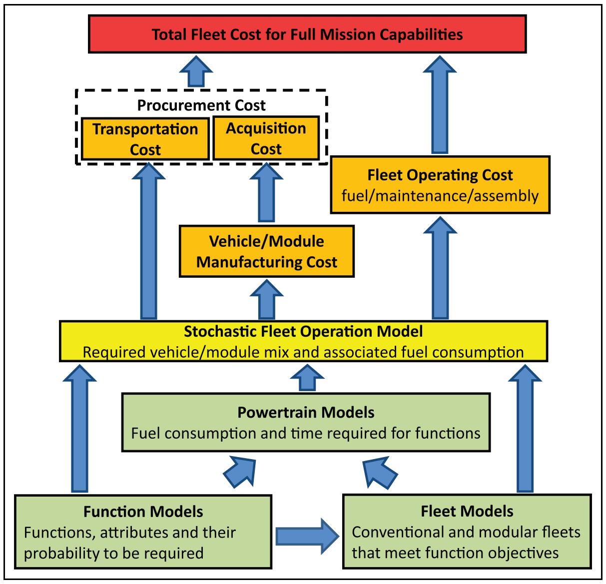

Figure 2. Overview of the modeling approach for analysis of conventional and modular fleets.

functions. First, the fleet and function models are discussed. Then, we will explain how each vehicle in the conventional and modular fleet is evaluated in performing its function. Next, the fleet operation simulation is detailed followed by a summary of the cost models. Finally, an overall comparison and analysis of the two fleets is given.

An overview of how all these models fit together to generate the data for the case study is shown in Figure 2. It should be noted that much of the underlying data is not based on actual military data. The purpose of the case study is to illustrate the utility of the tool and how such a comparison could be made to evaluate different fleet establishment strategies.

3.1. Case study: Function and fleet models

In order to compare the performance of the two fleets, a set of possible functions are defined. In this particular case study, five different function types were created based on vehicles currently in service: ambulance, combat, supply, troop, and scout. Each function type has a terrain-speed profile and four numerical attributes: maximum grade, maximum range, maximum payload, and curb weight. The function attributes were chosen according to characteristics of the conventional vehicles that take part in a given function. The maximum grade, range and payload were used as performance requirements to pinpoint vehicles capable of satisfying the load specifications of the function. The curb weight was used as a substitute for the survivability requirements since survivability has previously been correlated with curb weight.[22] The values and ranges of the functions were chosen from the conventional fleet since those vehicles are generally designed to meet specific functions. The breakdown of the function types, numerical attributes, and the conventional vehicles used in the case study are summarized in the Appendix, Table 5.

The goal of modularization is to reduce the cost and deployment time subject to meeting the same operational needs, i.e., the modular fleet must fulfill the same functions as the conventional fleet, while reducing cost and deployment time. Theoretically, the modular designs can be determined by solving an optimization problem with operational constraints. However, in this study, only one case of modularization is considered where the selection of modules was not determined through any optimization process.

To define the modules, a conventional vehicle was decomposed into five components: engine, transmission, suspension, tire and body. This decomposition could have been made in different ways depending on the level of detail desired in the analysis. The body can be further decomposed into chassis and body frame, while armor can be separated from the frame for additional components. Given this functional decomposition of a vehicle, a module can be defined either as a component or a combination of the components. As increased complexity does not add fidelity in demonstrating the utility of the framework and methodology, every component is simply defined as a module, and we limit the decomposition of the vehicle to the five aforementioned components.

The specific modules and their variants were developed by decomposing the baseline fleet into the five module types and recording each variant. Variants with similar performance specification and no quantifiable variation in adaptability or cost were collapsed into a single variant to reduce redundancy. The module types and number of variants in the case study are summarized in the Appendix, Table 6.

3.2. Case study: Function evaluation

After the functions and fleets are defined, the completion of each function by the vehicles in the fleets must be evaluated. This is done by calling a performance simulation model. These are often high fidelity models used during vehicle design, such as FEA model or vehicle dynamics models. The specific types of model and number of models is determined based on the goals of the study, availability of the models, and the run time of the simulations. The ability to integrate any number of these high fidelity design models is one of the greatest strengths of the framework.

In the case study, an AMESim power-train model[23] was used to estimate the fuel consumption and time the vehicles take to complete each function. The four function

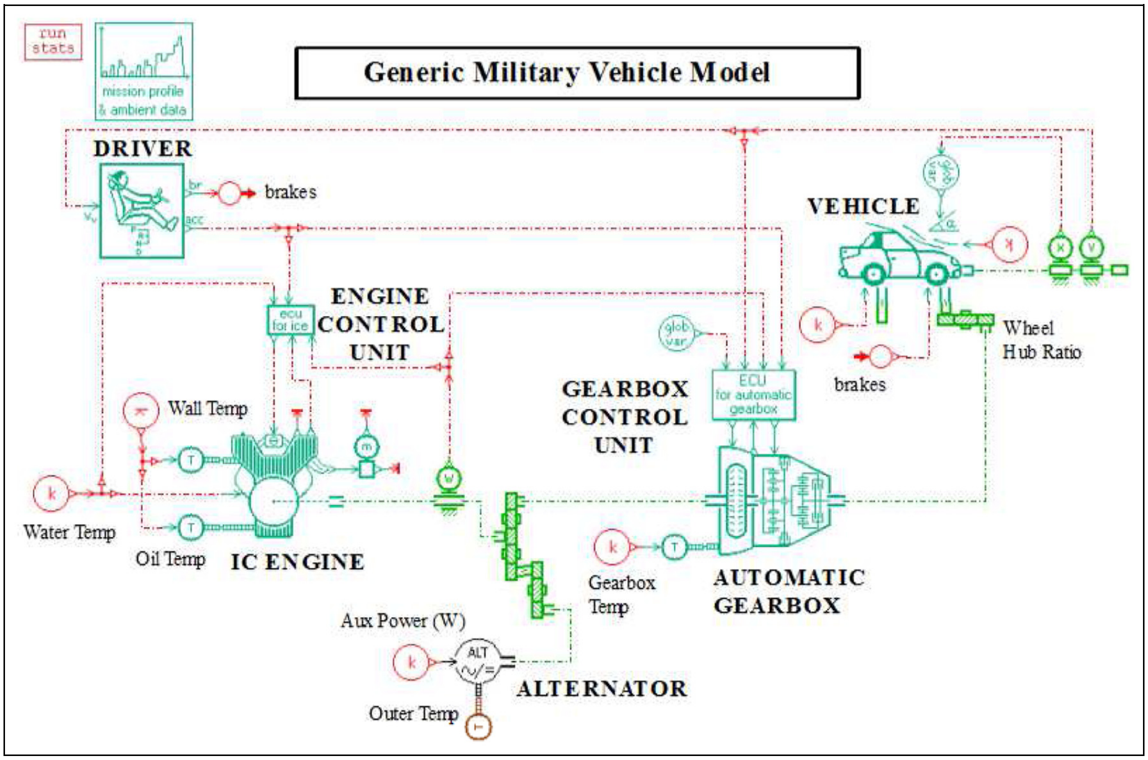

Figure 3. Vehicle and powertrain model for estimating time and fuel consumption.

attributes (gradeability, range, payload and curb weight) and terrain-speed profile are inputs to the power-train model (see Figure 3). The model includes a ''driver'' who calculates the necessary acceleration and brake commands to follow the terrain-speed profile. Based on those commands, a map-based engine model together with a control unit calculate the fuel consumption and engine torque used to drive the alternator and the gearbox. The alternator simulates the auxiliary loads which are constant for all functions. The automatic gearbox (which is a separate module from the engine) shifts the gears based on engine speed and transmits the torque to the vehicle model. Finally, the vehicle model calculates the speed and position of the vehicle by considering the rolling friction, aerodynamic drag and the total mass of the vehicle. The mass of the vehicle is the sum of all the module weights.

Running the high fidelity simulation model during each fleet operation model is not feasible due to the large number of simulations. In order to reduce the overall runtime, the vehicle performance (mpg, time to complete function) was computed for each conventional vehicle as well as for all possible modular vehicle configurations for every function type and attribute combination (subject to successfully completing the mission). The resulting matrix is then used by the fleet operation simulation to compute the time and fuel consumption of the conventional and modular fleets. This greatly shortened the overall fleet operation simulation time.

3.3. Case study: Fleet operation simulations

The fleet operation simulation requires certain input information for both the modular and the conventional fleets. First a set of functions that occur randomly or due to a trigger must be defined. Consider a simple fleet with four functions (ambulance, combat, scout and supply). Some of the basic information needed for each of these functions is shown in Table 1.

Each function has a probability of being called and may be checked at each or every *n*th time step. Certain functions, such as the supply function, have a 100% chance of being called once a week ($7 \times 24 = 168$ hours) and a 0% probability of being called at any other time. Other functions, such as the scout function, have a 10% chance of occurring every hour. The lowest level time increment is one hour. The average length and standard deviation of time it takes to complete each function is also specified. The specific length of time for each vehicle-function combination is calculated by using the vehicle model in the previous subsection. Lastly, a damage probability was assigned to each function to determine the likelihood the system component is damaged. A damaged component is

Table 1. Input information for each function.

Function details	Ambulance	Combat	Scout	Supply
Probability	0.0002	0.08	0.1	1
Time to check (hrs)	1	1	1	168
Avg. length (hrs)	3	7	4	15
Std in length (hrs)	1	2	2	5
Combat probability	0.02	1	0.2	0.01

Table 2. Probability of a function triggering another function.

Triggered Functions	Ending Functions			
	Ambulance	Combat	Scout	Supply
Ambulance	0	0.1	0.0001	0.0001
Combat	0	0.1	0.002	0.0001
Scout	0	0.05	0.01	0.01
Supply	0	0	0	0

assumed to be not functional at the completion of the function and will need to be repaired or replaced.

As mentioned previously, a completed function may trigger subsequent functions. Table 2 presents the probability of a function being triggered due to the completion of another function. The case study assumes that an ambulance function does not trigger subsequent functions, while a supply function cannot be triggered by any other function because it occurs independently on a weekly schedule. It should be noted that these probabilities are not based on actual military experience and are only for demonstration of the framework within the case study.

The amount of fuel, conventional vehicles or modules required to complete each function must be specified. The resources needed for the conventional and modular fleet is given in Tables 3 and 4, respectively.

The case study evaluated four different mission scenarios. The case study input information for the four fleet missions is given in the Appendix, Tables 7–9. Each scenario has a different set of function call probabilities. The probability of combat for a function, the module damage probability when in combat, and the resources required for each function are the same across all mission scenarios. The probability of a function being triggered by another function was generated randomly for each fleet mission. The time to complete each function and the fuel consumption were computed from the vehicle and powertrain models. The types of engines, tires, suspensions, and transmissions for each modular vehicle were determined based on the powertrain models to minimize the fuel consumption while following the terrain-speed profile.

The stochastic fleet model executes a single mission scenario according to Figure 1. One hundred realizations

Table 3. Conventional resources needed to complete functions.

Resources	Ambulance	Combat	Scout	Supply
Ambulance	1	0	0	0
Tank	0	1	0	0
Truck	0	0	1	0
Fuel Tanker	0	0	0	1
Fuel (gallons)	10	20	10	50

Table 4. Modular resources needed to complete functions.

Resources	Ambulance	Combat	Scout	Supply
Body Module 1	1	0	0	0
Body Module 2	0	1	0	0
Body Module 3	0	0	1	0
Body Module 4	0	0	0	1
Engine 1	1	0	1	0
Engine 2	0	1	0	1
Transmission 1	1	0	1	0
Transmission 2	0	1	0	1
Fuel (gallons)	8	15	12	50

were run for each scenario. The time steps for the analysis were one hour increments with a total time horizon of one year (8760 time steps). In order to complete a one year study with 8760 time steps it takes approximately 100 seconds for a single mission scenario on a Windows 3.6 GHz intel core *i*7 computer with 16 GB of RAM on a single core. The stochastic dynamic analysis algorithm can take advantage of parallel computing for larger studies to dramatically reduce the computational time. The simulations are run according to the data described in the tables in the Appendix. The simulation computes the optimal vehicle or module mix necessary for the fleet to complete all functions over the year. In other words, there are no constraints put on the fleet. The fleets grow over time based on the functions, and can only shrink through damage in combat. There is never any shortage of parts or supplies.

The fleet simulation output includes a log of each function called at each time step for every realization. This information, combined with information regarding which vehicles and modules were used at each time instance, serves as input to the cost models.

3.4. Case study: cost models

The cost model consists of a vehicle acquisition cost, a transportation cost, and an operational cost (maintenance and repair).

3.4.1. Acquisition cost considering manufacturing.

Manufacturing cost plays a critical role in affecting the product acquisition cost. For a civilian sedan, the manufacturing cost can constitute 50% of the Manufacturers Suggested Retail Price (MSRP).[24] Implementing a modular concept for vehicle fleet design has the potential to impact manufacturing cost, which in turn affects acquisition cost (or MSRP). For a modular vehicle fleet, most vehicles are derived from a common vehicle platform and use similar/shared production processes. As such, it is likely that the manufacturing cost of modular fleets could be reduced through resource sharing on the same production line. However, vehicle variety in a modular fleet could lower the manufacturing productivity if all the variants are machined/assembled on the same line, thus increasing the manufacturing cost (per unit time). Therefore, the analysis of final manufacturing cost for the modular fleet needs to consider a trade-off between cost reduction through resource sharing and cost increase due to productivity loss. This section proposes a method based on simulation to estimate the production cost for the components in a modular fleet which will be compared with the cost of the conventional fleet.

Extensive cost estimation approaches have been developed for manufacturing. Product designs and features were major factors considered in the manufacturing cost estimation.[25–28] Activity-based cost estimation is also a popular approach.[29,30] Other issues, such as concurrent product design and manufacturing,[31] and quality and flexibility[32] were also considered in manufacturing cost modeling. A review of cost estimation techniques was completed by Niazi et al.[33] To facilitate a quick cost evaluation for the modular vehicle fleet, this section adopts a simplified approach that estimates the average cost model based on productivity simulation and total cost of various activities/operations during manufacturing.

Each vehicle component in a conventional fleet such as the engine and the transmission is assumed to be produced on a dedicated line. In a conventional fleet, there is no common product platform and each type of vehicle is unique. Due to a lack of component sharing, multiple dedicated production lines should be employed to produce the different vehicle components. The dedicated line shows characteristics of high production throughput, low maintenance cost, and limited flexibility for product variety. Figure 4 shows an example of engine production through dedicated lines.

The acquisition cost for the conventional fleet is estimated by summing up the cost for all the vehicles in the fleet. Since the purchase cost for each vehicle is directly available from military vehicle suppliers' data catalogs, these cost data can be used in the analysis and no production simulation needs to be implemented. In addition, the cost data can be used to calibrate the parameters in the simulation models for the modular fleet, such as labor and equipment cost.

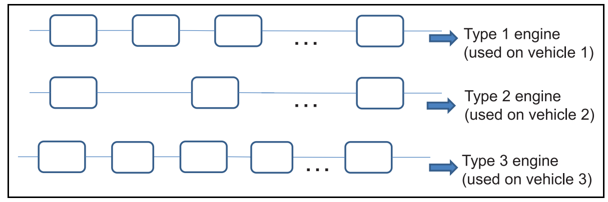

Figure 4. An example of dedicated lines for engine production.

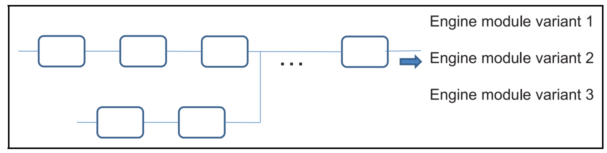

Figure 5. An example of modular engine production.

The vehicle components in a modular fleet should be designed as product families[34] (vehicle modules) to enhance interchangeability and reduce maintenance complexity. For example, different engine products employed on multiple vehicles are designed as module variants in one single product family where many components among different variants are similar and/or interchangeable. To deal with multiple variants, vehicle manufacturers may reconfigure their existing production lines into a mixed-model production line (Figure 5). Compared with a dedicated line, each machine in a mixed-model line needs to perform multiple tasks associated with different module variants, thus increasing the average cycle time for each vehicle component and decreasing the productivity. The main benefit of using these mixed model lines over dedicated lines is that fewer manufacturing lines are needed which results in a large savings in investment cost.

The acquisition cost for a modular fleet can be estimated by the sum of the cost for all vehicle modules. Based on the production line model described above, this analysis estimates the production cost of each vehicle module including engine, transmission, body and chassis, suspension, and tire. The cost estimation can be made by comparing the manufacturing cost (including investment on equipment and operating cost) with manufacturing throughput (productivity), that is:

$$\text{Manufacturing cost} = \frac{\text{Avg. production cost/time}}{\text{Avg. production rate}} \quad (2)$$

In Equation (2), the production rate can be obtained by simulating the mixed-model production line for each vehicle module. Commercial software packages such as WITNESS, ProModel, or ARENA can be employed to build the simulation model. The production cost includes equipment/machine acquisition and operating cost, labor cost, and product variant changeover cost. The average production cost and average production rate can be obtained by estimating overall production cost and output modules over a certain period of time. The final acquisition cost can be roughly estimated as a percentage of the manufacturing cost in MSRP as reported in Cuenca et al.[24]

In general, the manufacturing shows the experience curve effect, i.e., manufacturing cost will decrease by a certain percentage when the cumulative production doubles due to improvement in various aspects such as labor efficiency, methods, better equipment use and/or experience sharing. As such, the manufacturing cost can be assumed as a function of cumulative production volume in Equation (2), e.g., $C(n) = C_1 n^{-a}$,[35] where C is related to the production cost per unit time after a certain amount of parts are produced. For modular vehicles, due to the communalization in the production line, each worker gains more exposure to the same module and thus the learning curve effect could be significant in cost reduction.

In the case study, the acquisition cost for the conventional fleet is estimated for 22 types of vehicles, three types of suspensions, four types of tires, and fuel (diesel). The result is compared with the modular fleet which consists of 22 types of vehicle bodies, three types of engines, three types of manual transmissions, three types of suspensions, four types of tires, and fuel.

A mixed-model line for a modular fleet can reduce the investment cost in equipment and labor when product variety increases. However, the production lines can be slowed down due to competition for resources and changeover between different product variants. Adoption of modularity may either increase or reduce the manufacturing cost of each vehicle module/component.

3.4.2. Transportation cost. The case study transportation cost model and parameters were adopted from Farrar and Lloyd,[36] who addressed the transportation cost for the Afghanistan war. Although there are three methods of transportation (air, ground, and sea), this case study only considers the ground and sea cases. It is assumed that the Army requires the transportation of vehicles or modules to and from the theater. For transportation to the theater, ships transport the fleet to a port near the destination, and then heavy vehicles carry the fleet from the port to the theater. After completing the fleet mission, heavy vehicles carry the fleet back to the port, where the vehicles or modules are washed and inspected before being shipped back to the US. Applying this transportation process, the transportation costs must consider two sea costs, two ground costs, and one wash and inspection cost. While air cost is significantly affected by the shipping weight, sea and ground costs can be estimated by shipping volume.[36] For the calculation of sea and ground costs, measurement tons (M/T) were used: M/T = 40 cubic feet per ton (with 2240 lbs per ton).[37] The total transportation cost for the sea, ground, wash and inspection was calculated based on a rate per M/T, the vehicle weight and size, and labor hours.

3.4.3. Fleet operating cost. The operating cost model accounts for the fuel and maintenance costs of both conventional and modular fleets. For the modular fleet, there is also an additional cost of reconfiguring the fleet to meet the called function demands. The fuel cost is calculated based on the amount of fuel required to complete the fleet mission, which comes from the stochastic fleet operation model. In order to compute the maintenance cost, a weekly maintenance cost and schedule is assigned to each vehicle and module. Then, the maintenance cost is simply the sum over the entire fleet of the product of the unit maintenance cost and the number of weeks each vehicle or module is used. The unit maintenance costs for each vehicle and module are different and assumed to be proportional to the volume. In the case of the conventional fleet, when a spare part of a vehicle, such as a tire or a suspension is damaged, the cost of replacing those parts is added to the maintenance cost. If the damage to a vehicle is critical—i.e., the engine, transmission or body is damaged—the whole vehicle is replaced when a new function is called. By contrast, for the modular fleet, as an advantage of the modular architecture all modules are assumed to be replaceable with a new one when damage occurs. Also in the modular fleet, when a new set of functions are called, the current fleet is reconfigured to meet those new function demands. For that purpose, a modular vehicle can be reused, or modules removed and added to become a new vehicle. Modification of the modular fleet with minimum cost is calculated and included in the operating cost.

3.5. Case study: Fleet comparison

Figure 6 shows the total cost (acquisition, transportation, and operation) for both conventional and modular fleets. As throughout the case study, the values are not based on actual military costs and are for illustrative purposes only. Each mission scenario was run 100 times. Over the 100 realizations, the average total costs for each of the four mission scenarios were \$53M, \$55M, \$54M and \$66M for the conventional fleet and \$44M, \$45M, \$45M and \$49M for the modular fleet. This represents a 17–26% cost reduction for the modular fleet compared to the conventional fleet given the same fleet missions.

In this particular study, the manufacturing cost change for each vehicle component after adopting modularity is not a driving factor bringing down the acquisition cost for the entire fleet. It was found that the quantity of each

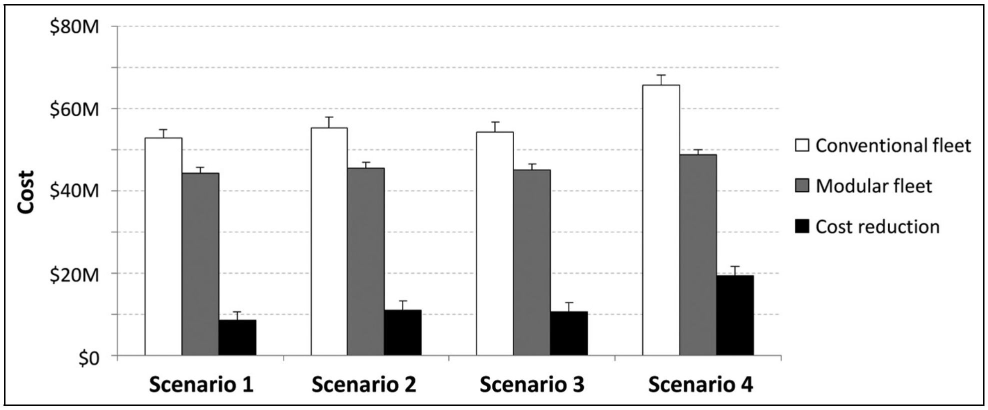

Figure 6. Cost comparison of conventional and modular fleets for four fleet missions.

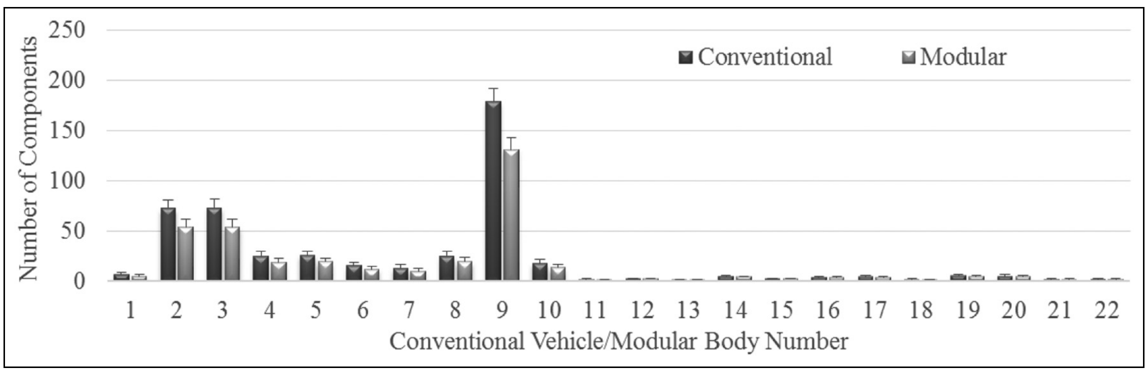

Figure 7. Conventional and modular vehicle fleet composition.

vehicle component such as the engine, transmission, body, or tire is significantly less than what is required by the conventional fleet. Thus, the reduction in the demand of vehicle components in the modular fleet masks the effect of the manufacturing cost change. Future study on manufacturing cost should investigate: (1) the relationship between the manufacturing/acquisition cost and delivery time based on simulation analysis, and (2) the impact of fleet modularity on supply chain design and acquisition cost. Either of these studies would also have to increase the fidelity of the transportation and logistics models to better capture military specific operational characteristics.

Figure 7 displays the composition of the conventional fleet and the corresponding modular bodies. Note that, for this case study there is a one to one correspondence of the modular vehicle bodies to the conventional vehicles. The plot shows that there are much fewer modular bodies required (there are also much fewer modular engines and transmissions that are needed). The composition of the fleet did not appreciably change across all four scenarios. This implies that the four scenarios did not differ significantly in their various function probabilities, particularly the combat and damage probabilities which were the same across all scenarios.

4. Conclusions

A new integrated approach for the design and analysis of a fleet was introduced. The details of the method can vary greatly by the application of the approach. The general outline of the approach is as follows.

1. Identify the tasks or functions that are expected to be carried out by the fleet. Include as much detail about the function needs as possible.
2. Select the systems and/or vehicles that will compose the fleet; a minimal composition of the fleet should be able to complete all of the expected functions. Multiple possible fleets can be selected for comparison purposes. The exact number and mix of systems or vehicles will be computed by the

simulation. This step is more of a system/vehicle design function.

3. Simulate the completion of each function by the vehicles and/or systems in the fleet. These models are usually the detailed vehicle performance simulation models developed during the vehicle design process.
4. Stochastically simulate the fleet operation using functions called on a stochastic or deterministic level to determine the needed supply of vehicles and/or systems to meet function demands.
5. Analyze the required number of systems and/or vehicles in each of the fleets to determine the overall cost of the fleets considering the acquisition, transportation, and fleet operating costs.

This approach to system design and analysis was illustrated on a fictitious case study comparing two military fleets. One of the fleets was a conventional fleet composed of vehicles currently available. The other fleet was composed of modules that were defined from a decomposition of the conventional fleet with redundancies eliminated. The modeling environment included high fidelity powertrain models to compute vehicle performance and fuel use on specific terrain-speed profiles, a stochastic simulation of fleet operations, and transportation, operating, and acquisition cost models. Technological feasibility of modularization is assumed. A significant cost savings was found when using the modular versus the conventional fleet.

There are a couple of limitations to the presented work. First, despite the advantage of parallel computing, the current framework is not feasible computationally for optimization. In particular, the stochasticity in the fleet operation simulation (Section 3.3, Case study: fleet operation simulations) would need to be handled by simplifying the model or building a surrogate model for optimization purposes. Second, the number of variables used in the function evaluation (Section 3.2, Case study: function evaluation) is limited because of the current need for a look-up table that is created by simulating all possible modular vehicle configurations, function types, and attributes. This approach is not feasible for a very large number of variables. Even if one can compute vehicle performance using a meta model, engineering constraints (mission completion) cannot be evaluated accurately.

There are several possible directions for future work and application of the framework. The first is to increase the fidelity of the results by working with the military and applying actual data (cost, scenario probabilities). This would also likely include expanding the number of functions, modules, and conventional vehicles. Also the transportation models would need to be expanded to include depot level, base level, and theater level repair and vehicle reconfiguration.

A second direction is to add more detailed performance models to the simulation to increase the fidelity of completing a mission. This would be necessary if the powertrain model alone was no longer an adequate performance model to determine the parameters of completing a mission. For example, if the combat function were to be expanded based on potential threats and threat environments, then the powertrain model alone (even with expanded terrain profiles) would be inadequate to determine the success of failure of a vehicle in combat.

A third direction would be to expand the simulation to compute more dependent variables, such as manpower needed to operate the fleet. This is of particular interest if modular autonomous systems (kits) have the potential of reducing the number of soldiers required in theater to complete missions.

As complex as the framework may appear to be, it is a powerful, flexible, and expandable tool with which it will be possible to understand the relative advantages and disadvantages of modularity for a military ground fleet.

Acknowledgements

The authors appreciate the advice and project support provided by Dr. Matthew Castanier at TARDEC, RDECOM. Reference herein to any specific commercial company, product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government of the Department of the Army (DoA). The opinions of the authors expressed herein do not necessarily state or reflect those of the United States Government or the DoA, and shall not be used for advertising or product endorsement purposes. UNCLASSIFIED: Dist A. Approved for public release.

Funding

The research was supported financially by the Automotive Research Center, a US Army Center of Excellence in Modeling and Simulation of Ground Vehicle Systems, headquartered at the University of Michigan in Ann Arbor, in partnership with TARDEC, Warren, Michigan.

References

1. SteadieSeifi M, Dellaert N, Nuijten W, et al. Multimodal freight transportation planning: A literature review. *Eur J Oper Res* 2014; 233(1): 1–15.
2. Wieberneit N. Service network design for freight transportation: A review. *OR Spectrum* 2008; 30(1): 77–112.
3. Sherali HD, Bae K-H and Haouari M. An integrated approach for airline flight selection and timing, fleet assignment, and aircraft routing. *Transportation Science* 2013; 47(4): 455–476.
4. Li Y, Miao Q and Wang BX. U.S. postal airmail routing optimization. Technical Report 13-4708, 2013. Washington, DC: Transportation Research Board of the National Academies, 2013.
5. Guerrero W, Prodhon C, Velasco N, et al. Hybrid heuristic for the inventory location-routing problem with deterministic demand. *Int J Prod Econ* 2013; 146(1): 359–370.
6. Ceder AA. Integrated smart feeder/shuttle transit service: simulation of new routing strategies. *J Adv Transport* 2013; 7(6): 595–618.
7. Ishii K. Life-cycle engineering design. *J Mech Des* 1995; 117(B): 42–47.
8. Bravo JJ and Vidal CJ. Freight transportation function in supply chain optimization models: A critical review of recent trends. *Expert Syst. Appl*. 2013; 40(17): 6742–6757.
9. Ballou PJ. Ship energy efficiency management requires a total solution approach. *Mar Technol Soc J* 2013; 47(1): 83–95.
10. Lin C, Wu T, Ou X, et al. Life-cycle private costs of hybrid electric vehicles in the current chinese market. *Energy Policy* 2013; 55(0): 501–510.
11. Chewning I and Moretto S. Advances in aircraft carrier life cycle cost analysis for acquisition and ownership decision-making. *Nav Eng J* 2000 112(3): 97–110.
12. Wilmering TJ and Ramesh AV. Assessing the impact of health management approaches on system total cost of ownership. In: *2005 IEEE aerospace conference (1–4)*, 5–12 March 2005, pp. 3910–3920. Big Sky, MT: IEEE.
13. Brunson K, DeLee B, Nachtigal J, et al. Case study: Transport carrier replacement analysis. *Eng Econ* 2011; 56(4): 354–384.
14. Shrake SO, Landis AE, Bilec MM, et al. A comparative analysis of performance and cost metrics associated with a diesel to biodiesel fleet transition. *Energy Policy* 2010; 38(11, SI): 7451–7456.
15. Fu L and Ishkhanov G. Fleet size and mix optimization for paratransit services. *Transp Res Rec* 2004; (1884): 39–46.
16. Mane M, Crossley WA and Nusawardhana SH. System of systems inspired aircraft sizing and airline resource allocation via decomposition. *J Aircraft* 2007; 44(4): 1222–1235.
17. Taylor C and de Weck OL. *Integrated transportation network design optimization*. Newport, RI: AIAA, 2006, pp.1–16.
18. Nusawardhana SH and Crossley WA. *Allocating variable resources over a finite time horizon to combine aircraft sizing and airline planning*. Arlington, VA: AIAA, 2005, pp.1–15.
19. Kim H and Hidalgo J. *System of systems optimization by pseudo-hierarchical multistage model*. Portsmouth, VA: AIAA, 2006, pp.1–14.
20. Patterson MD, Pate DJ and German BJ. Performance flexibility of reconfigurable families of unmanned air vehicles. *J Aircraft* 2012; 49: 1831–1843.
21. Mavris DN and DeLaurentis DA. Methodology for examining the simultaneous impact of requirements, vehicle characteristics, and technologies on military aircraft design. In: *22nd congress of the international council on the aeronautical sciences (ICAS)*. Harrogate, England, 27–31 August 2000, pp.1–10. Atlanta, GA: Georgia Institute of Technology.
22. Hoffenson S. *Safety considerations in optimal automotive vehicle design*. PhD Thesis, University of Michigan, USA, 2012.
23. LMS Imagine Lab. *AMESim*. http://www.plm.automation.siemens.com/en_us/products/lms/imagine-lab (accessed 10 June 2014).
24. Cuenca RM, Vyas AD and Gaines LL. *Evaluation of electric vehicle production and operating costs*. Argonne, Illinois: Citeseer, 1999.
25. Locascio A. Manufacturing cost modeling for product design. *Int J Flexible Manuf Syst* 2000 12(2): 207–217.
26. Ou-Yang C and Lin TS. Developing an integrated framework for feature-based early manufacturing cost estimation. *Int J Adv Manuf Technol* 1997; 13(9): 618–629.
27. Jung J. Manufacturing cost estimation for machined parts based on manufacturing features. *J Intell Manuf* 2002; 13: 227–238.
28. Duverlie P and Castelain JM. Cost estimation during design step: Parametric method versus case based reasoning method. *Int J Adv Manuf Technol* 1999; 15(12): 895–906.
29. Ozbayrak M, Akgun M and Turker AK. Activity-based cost estimation in a push/pull advanced manufacturing system. *Int J Prod Econ* 2004; 87(1): 49–65.
30. Ong NS. Manufacturing cost estimation for PCB assembly: An activity-basedased approach. *Int J Prod Econ* 1995; 38(2–3): 159–172.
31. Shehab E and Abdalla H. Manufacturing cost modelling for concurrent product development. *Rob Comput Integr Manuf* 2001; 17(4): 341–353.
32. Son YK. A cost estimation model for advanced manufacturing systems. *Int J Prod Res* 1991; 29(3): 441–452.
33. Niazi A, Dai JS, Balabani S, et al. Product cost estimation: Technique classification and methodology review. *J Manuf Sci Eng* 2005; 128(2): 563–575.
34. Simpson TW, Siddique Z and Jiao R. *Product platform and product family design – methods and applications*. New York, NY: Springer, 2006.
35. Grant RM. *Contemporary strategy analysis*. 5th ed. Malden, MA: Blackwell Publishing, 2004.
36. Farrar JP and Lloyd JP. *Fully burdened cost of retrograde, redeployment, reconstitution, and reset and analysis of alternatives (FBCR4 & AoA): New model to formulate strategic decisions for deployed ground vehicle equipment*. Technical Report no. NPS-LM-12-177, November. 2013, Monterey, CA: Naval postgraduate school.
37. USTRANSCOM. United States Transportation Command: Annual Report. Universal Service Contract (USC)-7, http://www.sddc.army.mil/GCD/International%20Cargo%20Distribution/UNIVERSAL%20SERVICE%20CONTRACT%20(USC)-7/USC-7%20(Conformed%20Copy%2017%20April%2014).pdf (2014, accessed 25 June 2014).

Author Biographies

Kiran D'Souza is an Assistant Professor at The Ohio State University in the Mechanical and Aerospace Engineering Department. He was previously an Assistant Research Scientist at the University of Michigan.

Alparslan Emrah Bayrak is a Research Fellow at the University of Michigan in the Mechanical Engineering Department.

Namwoo Kang is a Research Fellow at the University of Michigan in the Mechanical Engineering Department.

Hui Wang is an Assistant Professor at Florida State University and Adjunct Research Scientist at the University of Michigan.

Berk Altin is a Graduate Research Assistant at the University of Michigan.

Kira Barton is an Assistant Professor at University of Michigan in the Mechanical Engineering Department.

Jack Hu is the J. Reid and Polly Anderson Professor of Manufacturing, Vice President for Research, and Professor of Mechanical Engineering and Industrial and Operations Engineering at the University of Michigan.

Panos Papalambros is a James B Angell Distinguished University Professor of Engineering, Donald C Graham Professor of Engineering, Professor of Mechanical Engineering, and Chair of the Department of Integrative Systems and Design at the University of Michigan.

Bogdan I. Epureanu is a full Professor in the Mechanical Engineering Department at the University of Michigan.

Richard Gerth is in the Ground System Survivability group of the Tank Automotive Research, Development, and Engineering Center, US Army – RDECOM. —

Appendix: Case study input information

Table 5. Functions, function attributes and conventional vehicles used in the case study.

Function #	Function Type	Payload (lbs)	Max Grade (%)	Range (mi)	Curb Weight (lbs)	Vehicle
1	Ambulance	1000	60	50	7770	M997P1
2	Ambulance	1000	60	100	7770	M997P1
3	Ambulance	1000	60	250	7770	M997P1
4	Ambulance	1500	60	50	7770	M997P1
5	Ambulance	1500	60	100	7770	M997P1
6	Ambulance	1500	60	250	7770	M997P1
7	Ambulance	3000	60	50	7770	M997P1
8	Ambulance	3000	60	100	7770	M997P1
9	Ambulance	3000	60	250	7770	M997P1
10	Combat	2500	40	100	10300	M1151P1
11	Combat	2500	40	200	10300	M1151P1
12	Combat	5000	40	100	8150	M1151A1
13	Combat	5000	40	200	10300	M1151A2
14	Combat	2000	60	100	6780	M1025
15	Combat	2000	60	250	6780	M1025
16	Combat	3000	60	100	6780	M1025A2
17	Combat	3000	60	250	6780	M1025A2
18	Combat	3000	60	400	29260	M1117
19	Combat	5000	60	100	6051	M1121P1
20	Combat	5000	60	250	6051	M1121P1
21	Combat	12500	60	100	38000	JERRV
22	Combat	12500	60	250	38000	JERRV
23	Scout	1000	60	50	9800	M1114
24	Scout	1000	60	100	9800	M1114
25	Scout	1000	60	250	9800	M1114
26	Scout	1500	60	50	9800	M1114
27	Scout	1500	60	100	9800	M1114
28	Scout	1500	60	250	9800	M1114

(continued)

Table 5. (Continued)

Function #	Function Type	Payload (lbs)	Max Grade (%)	Range (mi)	Curb Weight (lbs)	Vehicle
29	Scout	3000	60	50	6400	M1113
30	Scout	3000	60	100	6400	M1113
31	Scout	3000	60	250	6400	M1113
32	Scout	3000	60	50	6400	M1113
33	Scout	3000	60	100	6400	M1113
34	Scout	3000	60	250	6400	M1113
35	Supply	40000	25	250	30,270	M920
36	Supply	1500	60	100	8200	M966P1
37	Supply	1500	60	200	8200	M966P1
38	Supply	3000	60	100	5900	M1008
39	Supply	3000	60	200	5900	M1008
40	Supply	5000	60	350	18181	M1079A1
41	Supply	10000	60	250	21470	M923
42	Supply	27000	60	250	39,600	M985P1
43	Troop	2000	60	300	5380	M1038
44	Troop	4000	60	250	5600	M1097
45	Troop	5000	60	275	5380	M998
46	Troop	5000	60	375	16699	M1078
47	Troop	10000	60	300	20939	M1093A1P1
48	Troop	10000	60	400	13530	M35A2

Table 6. Modular variants used to complete all functions in the case study.

Module Type	Variant
Engine Module	8.9 L, 300 kW
	15.2 L, 450 kW
	18.1 L, 520 kW
Transmission Module	5 speed
	6 speed
	7 speed
Suspension Module	Light Duty, 7 Leaves
	Medium Duty, 9 Leaves
	Heavy Duty, 10 Leaves
Wheel/Tire Module	9R16
	12R20
	16R20
	18R20
Body Module	Ambulance (1 variant)
	Combat (7 variants)
	Supply (6 variants)
	Troop (6 variants)
	Scout (2 variants)

Table 7. Input information for the fleet operation simulation for the four mission scenarios.

Functions	Probability of call - Scenario 1	Probability of call - Scenario 2	Probability of call - Scenario 3	Probability of call - Scenario 4	Time (s)	# of tires & suspensions	Suspension type	Probability of combat
Ambulance 1	0.0050	0.0004	0.0008	0.0014	4420	4	1	0.1
Ambulance 2	0.0010	0.0017	0.0032	0.0006	8840	4	1	0.1
Ambulance 3	0.0010	0.0005	0.0007	0.0006	22100	4	1	0.1
Ambulance 4	0.0040	0.0016	0.0027	0.0013	4420	4	1	0.1
Ambulance 5	0.0050	0.0011	0.0017	0.0028	8840	4	1	0.1
Ambulance 6	0.0060	0.0022	0.0029	0.0005	22100	4	1	0.1
Ambulance 7	0.0070	0.0011	0.0004	0.0003	4420	4	1	0.1
Ambulance 8	0.0080	0.0133	0.0050	0.0094	8840	4	1	0.1
Ambulance 9	0.0010	0.0000	0.0000	0.0000	22100	4	1	0.1
Combat 1	0.0300	0.0406	0.0478	0.0889	8840	4	1	1
Combat 2	0.0300	0.0403	0.0554	0.0698	17680	4	1	1
Combat 3	0.0300	0.0368	0.0171	0.0108	8840	4	1	1
Combat 4	0.0300	0.0115	0.0184	0.0183	17680	4	1	1
Combat 5	0.0100	0.0088	0.0105	0.0161	8840	4	1	1
Combat 6	0.0100	0.0082	0.0112	0.0139	22100	4	1	1
Combat 7	0.0100	0.0158	0.0114	0.0098	8840	4	1	1
Combat 8	0.0100	0.0060	0.0012	0.0008	22100	4	1	1
Combat 9	0.0120	0.0215	0.0010	0.0002	35360	4	3	1
Combat 10	0.0050	0.0021	0.0034	0.0065	8840	4	1	1
Combat 11	0.0050	0.0080	0.0019	0.0005	22100	4	1	1
Combat 12	0.0100	0.0087	0.0011	0.0013	12566	6	3	1
Combat 13	0.0100	0.0052	0.0048	0.0037	31415	6	3	1
Scout 1	0.0500	0.0783	0.0213	0.0075	4420	4	1	0.4
Scout 2	0.0600	0.0713	0.1075	0.1145	8840	4	1	0.4
Scout 3	0.0700	0.0221	0.0088	0.0111	22100	4	1	0.4
Scout 4	0.0800	0.1295	0.2087	0.2352	4420	4	1	0.4
Scout 5	0.0500	0.0731	0.0812	0.1242	8840	4	1	0.4
Scout 6	0.0600	0.0122	0.0044	0.0049	22100	4	1	0.4
Scout 7	0.0040	0.0044	0.0078	0.0123	4420	4	1	0.4
Scout 8	0.0050	0.0066	0.0118	0.0203	8840	4	1	0.4
Scout 9	0.0050	0.0093	0.0136	0.0255	22100	4	1	0.4
Scout 10	0.0090	0.0043	0.0050	0.0018	4420	4	1	0.4
Scout 11	0.0040	0.0034	0.0002	0.0004	8840	4	1	0.4
Scout 12	0.0070	0.0097	0.0080	0.0156	22100	4	1	0.4
Supply 1	0.0040	0.0011	0.0005	0.0002	31415	6	3	0.02
Supply 2	0.0040	0.0002	0.0003	0.0006	12566	4	1	0.02
Supply 3	0.0080	0.0034	0.0020	0.0004	25132	4	1	0.02
Supply 4	0.0040	0.0019	0.0005	0.0002	12566	4	1	0.02
Supply 5	0.0006	0.0008	0.0010	0.0013	25132	4	1	0.02
Supply 6	0.0400	0.0494	0.0389	0.0659	43981	4	2	0.02
Supply 7	0.0090	0.0141	0.0274	0.0469	31415	6	2	0.02
Supply 8	0.0400	0.0670	0.0855	0.0330	31415	8	3	0.02
Supply, troop 1	0.0400	0.0349	0.0454	0.0815	37698	4	1	0.02
Supply, troop 2	0.0040	0.0018	0.0023	0.0012	31415	4	1	0.02
Supply, troop 3	0.0600	0.1068	0.0593	0.0240	34556.5	4	1	0.02
Supply, troop 4	0.0400	0.0405	0.0156	0.0188	47122.5	4	2	0.02
Supply, troop 5	0.0040	0.0047	0.0060	0.0068	37698	6	2	0.02
Supply, troop 6	0.0058	0.0107	0.0179	0.0205	50264	6	2	0.02

Table 8. Mapping of the needed modules for each function.

	Function Number																																														
Modules	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
Body 1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Body 2	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Body 3	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Body 4	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Body 5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Body 6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Body 7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Body 8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Body 9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Body 10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Body 11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Body 12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
Body 13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0
Body 14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Body 15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Body 16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Body 17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Body 18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Body 19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Body 20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Body 21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Body 22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Suspension 1	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	0	4	4	0	0	4	4	4	4	4	4	4	4	4	4	4	4	0	4	4	4	4	0	0	0	4	4	4	0	0	0
Suspension 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	6	0	0	0	0	4	6	6
Suspension 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	6	6	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	8	0	0	0	0	0	0
Tire 1	0	0	0	0	0	0	0	0	0	4	4	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tire 2	0	0	0	0	0	0	4	4	4	0	0	4	0	0	0	0	0	0	0	0	0	0	4	4	4	0	0	0	4	0	4	4	0	4	0	4	4	0	0	0	6	0	4	4	4	4	0	0
Tire 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	4	4	4	4	6	6	0	0	0	4	4	4	0	4	0	0	4	0	6	0	0	4	4	4	0	8	0	0	0	0	6	6
Tire 4	4	4	4	4	4	4	0	0	0	0	0	0	0	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Engine 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Engine 2	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	1	1	1	1	1	1
Engine 3	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0
Transmission 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	1
Transmission 2	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0
Transmission 3	1	1	1	1	1	1	1	1	1	0	0	1	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	0	1	1	1	1	0	0	0

Table 9. Probability of damage in each module component if there is combat and whether the component damage would scrap the whole vehicle in the conventional case.

Module	Probability of damage when in combat	Important enough to scrap whole vehicle (yes=1, no=0)
Body 1	0.1	1
Body 2	0.1	1
Body 3	0.1	1
Body 4	0.1	1
Body 5	0.1	1
Body 6	0.1	1
Body 7	0.1	1
Body 8	0.1	1
Body 9	0.1	1
Body 10	0.1	1
Body 11	0.1	1
Body 12	0.1	1
Body 13	0.1	1
Body 14	0.1	1
Body 15	0.1	1
Body 16	0.1	1
Body 17	0.1	1
Body 18	0.1	1
Body 19	0.1	1
Body 20	0.1	1
Body 21	0.1	1
Body 22	0.1	1
Suspension 1	0.01	0
Suspension 2	0.01	0
Suspension 3	0.01	0
Tire 1	0.05	0
Tire 2	0.05	0
Tire 3	0.05	0
Tire 4	0.05	0
Engine 1	0.02	1
Engine 2	0.02	1
Engine 3	0.02	1
Transmission 1	0.02	1
Transmission 2	0.02	1
Transmission 3	0.02	1