# A Vector Approach to Assessing Modularity

Amie C. Stryker
David R. Jacques
David S. Long
Department of Systems & Engineering Management
Air Force Institute of Technology
2950 Hobson Way, WPAFB, OH 45433

**Abstract.** A method to assess product modularity using a vector approach is presented and demonstrated using two precision guided munitions. Modularity has several fundamental benefits agreed upon by industry including reusability, flexibility, reconfigurability and extensibility. Current modularity measures focus on interfaces within or between modules in provide/depend relationships. A new method that assesses the module interfaces as well as captures and addresses each of the recognized modularity benefits is presented in a Vector Modularity Measure (VMM). Components of the VMM include terms for degree of coupling, reusability, and flexibility. Flexibility is assessed in terms of reconfigurability and extensibility. The overall evaluation method is then summarized, followed by an application using two similar precision guided munitions in the U.S. Air Force inventory: the Guided Bomb Unit-24 (GBU-24), referred to as the laser guided bomb (LGB); and the Guided Bomb Unit-31 (GBU-31), referred to as the Joint Direct Attack Munition (JDAM).

## Nomenclature

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|---|---|
| $VMM$ | Vector Modularity measure. |
| $V$ | Degree of coupling between modules in a system. |
| $X$ | Reusability factor. |
| $Y$ | Reconfigurability factor. |
| $Z$ | Extensibility factor. |
| $n$ | Total number of modules in a product. |
| $n_{mp}$ | Number of modules used in multiple products. |
| $r$ | Number of configurations possible for a given $S$ and $t$ pair. |
| $r_{\text{act}}$ | Actual number of configurations realized |
| $s_i$ | Number of module options for the $i^{th}$ module. |
| $k_i$ | Number of module options selected out of $s_i$ for the $i^{th}$ module. |
| $S$ | Total number of module options across all modules with options. |
| $t$ | Total number of modules with options. |
| $\sigma$ | Standard deviation from the mean of all the modules with options in a product. |
| $a$ | Number of architectural options. |
| $m$ | Total number of functions. |
| $y_1$ | Average number of configurations per option. |
| $y_2$ | Average number of configurations per module with options or decision point. |
| $y_3$ | Percentage of a product that is reconfigurable. |
| $y_4$ | Realized percentage of maximum number of configurations possible. |

# Introduction

Product modularity has gained an increase in focus over the last couple decades. The benefits of modularity in product design have been widely recognized and qualitatively captured by Gershenson et al. (Gershenson 2003). Some of these benefits include changeability, flexibility, reusability, reconfigurability, and extensibility. Several measures exist to quantitatively assess the modularity of a product in terms of interfaces within and between modules which is referred to as degree of coupling in this paper (Mikkola 2007, Hölttä-Otto 2007, Sosa 2007 etc.). But, what does being modular really mean? When comparing the modularity between two products or two designs for a given product, what does it mean when the modularity measure indicates one is more modular than the other? A method to capture recognized benefits of modularity in a rigorous manner is proposed and then demonstrated using two precision guided munition examples.

When decision-makers or designers state they want a product to be more modular, they are indicating that there are one or more aspects of modularity that they want captured in a new design. Current modularity measures roll-up contributing factors to modularity which result in a real number between zero and one as the overall modularity value for a product (Mikkola 2007, Hölttä-Otto 2007, Sosa 2007 etc.). This methodology gives no additional insight into the aspects of modularity being realized. The Vector Modularity Measure (VMM) presented in this paper uses degree of coupling as well as the benefits of modularity, in a vector form, to highlight the contributing factors to a product's modularity assessment. Each of the equations used in the VMM can be used to gain insight into the specific modularity benefits being realized. Designers and decision-makers alike can use this insight to improve existing designs and to aid in overall product selection based on priorities and goals of modularizing a product.

# Background

Before introducing the Vector Modularity Measure, the analysis process, and the applications, a few key terms are introduced. The definitions given below are those of the authors, except where cited, for purposes of this paper and analysis.

**Modularity** - grouping of components into well defined entities, such as modules or sub-assemblies, that can be further described by the interfaces between them.

**Interface (I/F)** - spatial, informational, material, energy, or structural connection or coupling of one module to another module within a product (Sosa 2007). I/F types given below are defined similarly as in (Sosa et al. 2007).

- **Spatial I/F** - physical adjacency for alignment, orientation, serviceability, assembly or weight.
- **Informational I/F** - transference of signals or controls.
- **Material I/F** - transference of airflow, oil, fuel, or water.
- **Energy I/F** - transference of heat, vibration, electric, or noise energy.
- **Structural I/F** - transference of loads or containment.

**Module** - group of components or sub-assemblies that perform one or more functions

**Reusability** - ability of modules within a product to be used in at least one other product variant.

**Flexibility** - a product's ability to change or adapt to new requirements; it is measured in terms of a product's ability to be reconfigurable and extensible.

**Reconfigurability** - product’s ability to be assembled or built in multiple configurations according to its architecture.

**Extensibility** - built in architectural options for upgrading, or adding functionality to a product.

**Function** - technical process involving energy, material and/or signals being converted and/or channeled.

**Flow** - material, signal, and/or energy that can be converted or channeled.

The idea of measuring modularity is not new. Gershenson et al.(Gershenson 2004) reviewed the literature and summarized various methods for measuring modularity through 2004. Guo et al. (Guo and Gershenson 2003) extended the concept and compared the various modularity measures based on consistency and sensitivity analyses. Several methods have been proposed since 2004 by Mikkola (Mikkola 2007), Hölttä-Otto (Hölttä-Otto 2007), and Sosa et al. (Sosa 2007). These measures quantify the module-to-module connections, both inter- and intra-module, but ultimately focus on coupling of either design parameters or interfaces. Mikkola's measure accounts for a module's reusability in an exponent term identified as a substitutability factor. None of the measures, however, take into account the assumed benefits of modularity. While a common consensus exists on the benefits of modularizing a product, no method or measure captures these benefits.

## Vector Modularity Measure

**Measure Overview**. The Vector Modularity Measure (VMM) proposed herein captures the degree of coupling in a product along with the recognized benefits of modularity in a vector form for further mathematical manipulation. Specifically, the following aspects of modularity are captured in the VMM introduced here: degree of coupling between/among the modules in a system; reusability of the modules; and the flexibility of a product to adapt to changing requirements which is assessed in terms of its reconfigurability and extensibility. Equation (1) defines the Vector Modularity Measure, and subsequent subsections detail each of the factors comprising the VMM.

$$\boldsymbol{VMM} = [\, V,\ X,\ \boldsymbol{Y},\ Z \,] \tag{1}$$

where: $V$ = Degree of coupling
$X$ = Reusability
$\boldsymbol{Y}$ = Reconfigurability
$Z$ = Extensibility

The Vector Modularity Measure, VMM, is useful when comparing two similar products in terms of modularity. The composition of the VMM points to the benefits of modularity that are being realized for one product over another one. The measure is also useful when upgrading an existing product. The measure can be calculated for an existing product and then compared to iterations of proposed module designs. Does the new module design increase or decrease the degree of coupling? Is the new module reusable? Are there constraints on the interfaces that the module imposes that will limit its ability to be reconfigured with certain other modules in a product? All of these questions can be answered as a result of performing the VMM calculations. Another useful aspect of the VMM is that it focuses the designer's attention on the benefits of modularity which are the goals of modularizing a product in the first place. This focus of the designer's attention in and of itself is beneficial in increasing a product's modularity.

**Degree of Coupling.** The first factor in the VMM, the degree of coupling, *V*, is used to assess how connected/disconnected each module is from each of the other modules within a product. This factor can be used to identify which modules are loosely or highly coupled to the other modules in a product. This assessment can then be used by designers and decision-makers to guide future design decisions regarding which modules to target when trying to improve a product's modularity. For example, the interfaces that a module has to other modules imposes constraints on that module according to the product's architecture. These constraints have to be accounted for when redesigning the module. A module that is loosely coupled has fewer constraints than a module that is highly coupled from an interface viewpoint.

This idea of using degree of coupling is similar to the use of in- and out-degree modularity measures in Sosa et al. (Sosa 2007). Another similar concept is the non-zero fraction (NZF) term in the modularity measure of Hölttä-Otto et al. (Hölttä-Otto 2007). The NZF is useful in determining a product's connectedness or coupling and will be used in the modularity measure introduced in this paper. The NZF uses a symmetrical binary design structure matrix (DSM), an *n* x *n* matrix where each column and row refers to a module in a product. If an interface exists between two modules, then an “X” is used to indicate the interface. The NZF is then calculated as the ratio of the total number of non-zero entries to the total number of entries minus the diagonal entries, *n*.

For the VMM, a DSM is built for each of the five interface types (spatial, informational, etc.). However, the DSMs used herein accommodate directional interfaces by type and hence are generally nonsymmetric. The NZF is calculated for each of the five DSMs using Equation (2).

$$\mathrm{NZF} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} DSMij_{i\neq j}}{n(n-1)} \tag{2}$$

where: $n$ = Total number of modules in a product

The degree of coupling, *V*, between modules is then calculated by summing the five NZF terms over a product and dividing by the total number of interface types. The resultant ratio for the degree of coupling factor is the total number of interfaces divided by the total number of possible interfaces minus the diagonal entries over all five interface types. This calculation effectively results in averaging the NZF terms over the five interface types and is shown in Equations (3) and (4).

$$V = \frac{1}{5}\sum_{k=1}^{5} \mathrm{NZF_k} \tag{3}$$

$$= \frac{\sum_{k=1}^{5}\left(\sum_{i=1}^{n}\sum_{j=1}^{n} DSMij_{i\neq j}\right)_k}{5n(n-1)} \tag{4}$$

The analysis in this paper uses integer values when calculating *V*. The analysis can be extended to include the real domain as well. One benefit of this extension is that it accommodates the potential to evaluate design complexity. For example, if a real value is assessed to each interface based on the number of interfaces or the level of complexity for the interface type, Equation (4) would need to be slightly modified; the denominator would need to be removed that normalizes the term since the upper limit is no longer imposed on the number of interfaces. This extension as well as additional uses of Equation (4) are not expounded upon here but are stated for future research.

**Reusability.** The reusability factor, $X$, is an assessment of the percentage of modules of a product that are used in other products. In assessing the reusability of a product, modules are sorted into two categories: unique and reusable. This is similar to the categorization that Mikkola (Mikkola 2007) uses to categorize components. Mikkola identifies reusable components as standard components and then further categorizes each standard and unique components into customizable and noncustomizable components. In assessing reusability, it is not necessary to categorize modules beyond unique and reusable. In the reusability assessment, each module is assigned a binary value indicating whether or not it is used in at least one additional product. The values for the reusable modules are then summed across a product and divided by $n$ to attain the overall percentage of a product's module reuse.

$$X = \frac{n_{mp}}{n} \tag{5}$$

where: $n_{\text{mp}}$ = Number of modules used in multiple products

$n$ = Total number of modules

The reusability factor highlights to designers what percentage of a product is being reused. In order to claim the benefit of reusability, designers need to avoid or minimize using unique module designs where possible. For the analysis herein, assessing whether a product is reused or not is sufficient to glean the benefit of reusability being captured. Knowing the extent a module is reused, or the number of products containing the module, has potential benefits beyond the assessment in this paper. For example, as the number of products that use a given module increases, the probability that the module is or will become a standard module increases. A future adaptation could account for the number of products each module *option* (see Reconfigurability subsection) is used in when building variant configurations of a product. Using this adaptation, module options that are peculiar to a product (i.e. not reusable in other products) are highlighted. In the current assessment, however, they are hidden by the overall categorization of “unique/reusable” if a given module has multiple options and a subset of those modules are reusable.

**Flexibility.** The flexibility of a product is a measure of its ability to change or adapt to new requirements. Flexibility in this paper is assessed in terms of a product's ability to be reconfigurable and extensible with respect to its architecture. These two components of flexibility are described in the next two sections.

**Reconfigurability**. The definition of reconfigurability used in this analysis is a product’s ability to be assembled or built in multiple configurations according to its architecture. The authors hypothesized in (Stryker 2010) that a measure of reconfigurability of a product needs to take into account more than the number of (re)configurations made possible by module options. The reconfigurability measure (RM), previously developed by the authors (Stryker 2010) is used in this paper as part of the overall VMM, as the $\boldsymbol{Y}$ term. The reconfigurability factor, $\boldsymbol{Y}$, is defined by the four ratios given in Equations (6) and (7).

$$\boldsymbol{Y} = [\, y_1 \;\; y_2 \;\; y_3 \;\; y_4 \,] \tag{6}$$

$$= \begin{bmatrix} \dfrac{r}{S} & \dfrac{r}{t} & \dfrac{t}{n} & \dfrac{r}{r_{u.b.}} \end{bmatrix} \tag{7}$$

where:

$S = \sum_{1}^{t} s_i =$ Total number of module options
$n =$ Number of modules in a product
$t =$ Number of modules with options
$r =$ Number of configurations possible
$r_{u.b.} =$ Upper bound number of configurations for a given $S$, $t$ pair

A product is comprised of $n$ modules that are arranged according to a product's architecture. Each of the $n$ modules has one or more ways in which it interfaces with the rest of the product. Each of the $n$ modules may or may not have options to choose from when assembling the product. Each module that has options is counted in an $s_i$ term. The $s_i$ term represents the number of module options for the $i^{th}$ module where $1 \le i \le t$ such that $t$ is the total number of modules with options. The sum of the $s_i$ terms is equal to $S$ as shown above.

The mathematical number of reconfigurations made possible by each module option is the product of each of the $s_i$ terms assuming only one option for each module can be chosen, and no pairwise incompatibilities exist. The mathematical number of reconfigurations possible is used in conceptual design analysis as well as when in-depth knowledge of a product is not available. When possible, the actual number of configurations, $r_{\text{act}}$, should be used in an assessment to improve the quality of the RM. In reality, $r_{act} \le r$ due to pair-wise incompatibilities between option choices for the $i^{th}$ and $j^{th}$ modules.

Returning to Equations (6) and (7), the $y_1$ and $y_2$ ratios refer to the reconfigurability of a product design. Specifically, $y_1$ indicates the average number of reconfigurations made possible per option being maintained in inventory. The $y_2$ ratio is an indicator of the average number of configurations made possible per module with options. Alternatively, this second ratio can be assessed as the average number of reconfigurations made possible per decision point.

Whereas $y_1$ and $y_2$ are assessments of the current design, $y_3$ and $y_4$ are assessments of how configurable product design is compared to how reconfigurable it could be given its architecture. The $y_3$ term represents how much of a product is reconfigurable as well as the maximum $t$ achievable ($t \le n$) for the given product. The latter point is important since the number of reconfigurations possible is a function of $S$ and $t$. The $S$ and $t$ pair imposes an upper bound limit on the number of reconfigurations possible, $r_{\text{u.b.}}$. The last ratio, $y_4$, is an indication of how much of the $r_{\text{u.b.}}$ a product is achieving. When $y_3$ and $y_4$ are equal to one, then the current product design has maximized its reconfigurability for the given $S$ and $t$ pair. If either $y_3$ or $y_4$ (or both) is less than one, then the product is not maximizing the number of configurations possible and is not maximizing its reconfigurability. In order to maximize the number of reconfigurations for a given $S$ and $t$ pair, the standard deviation, $\sigma$, of the $s_i$ factors should equal zero (only possible if $S / t \in \square$) or be minimized.

Increasing the number of module options ($s_i$ and hence $S$) and increasing the number of modules with options ($t$), increases the combinations possible. The increased number of possible combinations or reconfigurations causes an overall increase in flexibility. If two products with the same $S$ and $t$ are assessed, the product with the lower $\sigma$ will in general have more reconfigurations possible and is considered more reconfigurable, and through extension, more flexible. In general, to maximize the number of possible reconfigurations, $r$, for a product, regardless of the $S$ and $t$ values, $\sigma$ should be minimized. It should be noted that $\sigma = 0$ may or may not be achievable since $s_i \in \square$, and generally $S/t \notin \square$.

The reusability factor only considers whether or not a module is reused. The reconfigurability factor takes into account the numerous modules that can fit within a product's architecture to form different reconfigurations. This factor implies that increased possible reconfigurations are better than fewer reconfigurations from a modularity viewpoint. That's not to say from a logistics viewpoint, from a configuration management viewpoint, or from an assembly time viewpoint that more is necessarily better. Further, operational or user needs will ultimately determine the number of reconfigurations that are needed.

**Extensibility.** Extensibility is a measure of a product's ability to be extended whether through adding functionality or upgrading existing functionality (Gerwin 1987). The latter component, upgrading functionality, is a characteristic of performance and is not assessed in the current measure. However, if a module has built-in architectural options that add functionality, then it will be included in the extensibility factor. For example, if a navigation module that provides position information is upgraded to increase the position accuracy, it still performs the same function and will not be included in the $Z$ factor. If the same navigation module has built-in architectural options to provide velocity information as well as position information, then the additional functionality will be included in the $Z$ factor. The additional product functionality previously mentioned is referred to here as architectural design options, $a$, similar to "hooks" and "scars" in software and hardware design respectively (Maier 2000), that allow for design evolution. They are the functions that will be performed by modules that may or may not exist, but are not in the current inventory of module options. When assembling products with one of the functions in the $a$ term, the product is considered to be built in an engineer-to-order framework. On the other hand, the modules that perform the $m$ functions are built in a configure-to-order framework since the module options are kept in inventory (Kratochvíl 2005). The extensibility factor in the VMM focuses on capturing the built-in architectural design options for adding anticipated functionality to a product as shown in Equation (8).

$$Z = \frac{a}{m}, \qquad 0 \le a \le m \tag{8}$$

where: $a$ = Number of anticipated architectural or functional options

$m$ = Total number of functions

The range for $a$ is assumed to be 0 – $m$. This range is based on the assumption that a product would not be fielded with less than 50% anticipated functionality. While $Z$ has no hard upper limit, it has a practical limit of 1 based on the previous assumption. This assumption is consistent with the cases analyzed in the Application section. Future use case analysis should be performed to confirm this assumption. $Z$ is a relative order of merit as it is a measure based on a percentage of original primary functionality. It is important to keep the functions in $a$ at the same level of abstraction as the functions in m and to follow Suh's independence axiom (Suh 1990). Assessing extensibility requires in-depth knowledge of a product's design. In cases where reverse-engineering is used to upgrade products, extensibility is harder to evaluate but is still an important benefit of modularity.

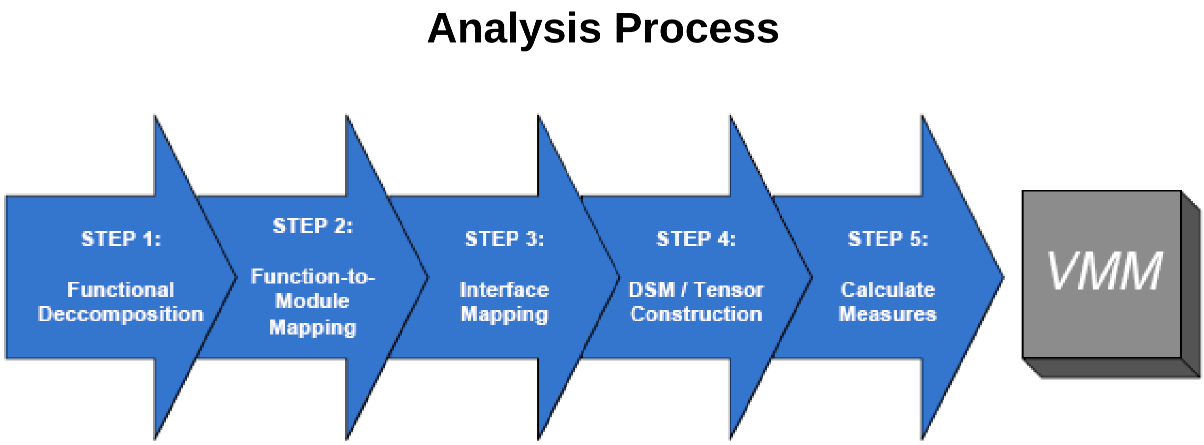


Figure 1.  Modularity measure analysis process

The analysis process used to calculate a product's VMM begins with a functional model that is accomplished through a functional decomposition of the product.  Hirtz et al. (Hirtz 2002) extended the previous work by Pahl and Beitz (Pahl 1996) to create a functional basis vocabulary. This vocabulary defines a standardized language to decompose a system into functions and flows to a level of abstraction needed for a given analysis.  Three levels of abstraction are used to describe the decomposition:  class (or primary), secondary, and tertiary.

Functional decomposition (Step 1) is not new.  Functional decomposition is typically done in the early stages of design conceptualization, transforming user requirements into functional requirements (Stone 2000, Suh 2001, Fixson 2005).  Functional decomposition begins at the top level outlining the overarching function of a product.  This overarching function is then decomposed into the three levels of abstraction listed above.  For the purposes of this analysis, the functional decomposition abstraction level stops at the class level.

After functional decomposition has been accomplished at the class level, a product's components and/or modules can be mapped (Step 2) to their corresponding function(s).  For existing products, one method to indentify module boundaries is to use reverse-engineering.  Even though the product exists, clear boundaries may not present themselves, requiring iterations of Step 2 until the boundaries are clearly defined.  For new products, identifying the module boundaries also will likely require several iterations of Step 2.  Another technique to identify modules is to use the dominant flow heuristic developed by Stone et al (Stone 1998, 2000a, 2000b).  This heuristic groups components performing similar functions into modules.  Iterations of Step 2 should continue until the function-to-module ratio is 1:1 or is minimized (Buede 2000).  The module-to-function ratio can be 1:1 or 1:many (Buede 2000).

Using the identified modules, a bipartite graph can be constructed and used to understand and illustrate the interface mapping (Step 3) between modules.  These interfaces, along with the functional decomposition, require in-depth subject or domain knowledge best gleaned from subject matter experts (SMEs).  The interfaces between the modules are categorized similarly as was done by Sosa et al. (Sosa 2007) into five categories - spatial, informational, material, energy, and structural. A design structure matrix (DSM) can be constructed (Step 4) with the identified modules as row and column labels. The five matrices (by interface type) can then be populated with the interface data. An optional tensor graphic can also be constructed to help illustrate the types and degree of interfaces (see Application section). Finally, assessment of the VMM (Step 5) of the product can begin starting with the degree of coupling, $V$. $V$ is an assessment of the connectedness/disconnectedness between and among the modules which is also considered the degree of coupling between and among the modules. After subtracting the diagonal entries in each of the five DSMs, Equation (4) can be used to solve for $V$ using the off-diagonal entries in the DSM.

The reusability factor, $X$, can be assessed using the modules identified in the DSM in previous steps. Each of the identified modules, at a minimum, is in the product being assessed. Additionally, the modules could be used in other products or product families. If a module is used in other products, then it is counted as 1. $X$ is the number of these modules divided by the total number, $n$, of modules. Keeping track of each module as being reused or unique is straight forward and the reusability factor is easy to calculate even for products with a large number of modules. At this point in the modularity assessment, however, it is worthwhile to keep a list of each module and its associated products. This tracking will aid in the reconfigurability assessment later in the modularity analysis as well as future adaptations of the reusability factor (see Reusability subsection).

To calculate the reconfigurability factor, $\boldsymbol{Y}$, more knowledge of the product architecture is needed. Each module in the product performs a function or multiple functions. In some cases, more than one option for a module can accomplish these functions and the designer or builder can choose from multiple module options when constructing the product. The number of options for each of these modules needs to be identified, starting with the modules identified in the DSM. The number of modules with multiple options, $t$, can then be identified as can $S$, the total number of options for modules with options. Using each of the $s_i$ terms, the number of reconfigurations and the standard deviation, $r$ and $\sigma$, respecitively, can then be calculated. Lastly, the four reconfigurability ratios can be calculated using Equations (6) and (7).

Lastly, extensibility, $Z$, can be calculated. The identification of additional architectural options requires in-depth knowledge of the architecture of the product under analysis. Each additional architectural option is counted and summed into $a$, which is then factored into $Z$ in Equation (8).

## Application

**Examples**. The modularity analysis process is demonstrated using two precision guided munitions (PGMs) in the Air Force inventory. The first PGM is the GBU-24, also referred to as a laser guided bomb or LGB. The second example is the GBU-31, also referred to as the Joint Direct Attack Munition or JDAM. Both munitions, shown in Figures 2 and 3 can use multiple bomb bodies as the main weapon module. The Mk 84, 2000 lb, general purpose bomb was used in this analysis for both PGMs. These two PGM examples were chosen for their similar modular architectures and continued use by the Air Force. Both munitions are mainstays in the Air Force weapons arsenal and have evolved over the years due to changing requirements, upgraded technologies, and employment effectiveness.

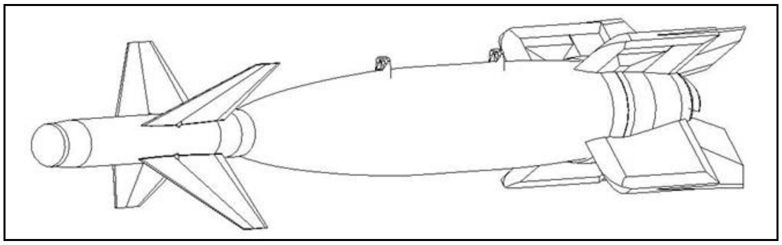


Figure 2. GBU-24 diagram, Mk 84 variant

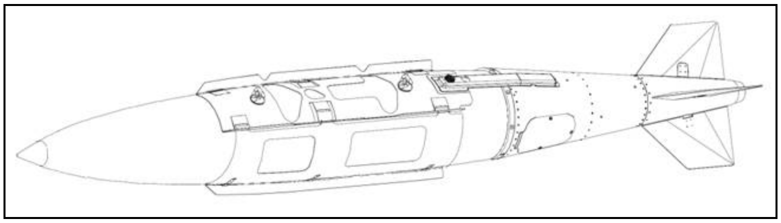


Figure 3.  GBU-31 diagram, Mk 84 variant

**GBU-24**.  The first step in the modularity analysis process is the functional decomposition or function structure.  Figure 4 depicts the GBU-24 function structure which is very similar for both munitions.  The functional basis language was used to represent the functional decomposition. The Appendix gives a lay translation from the functional basis language to a more general language.  For example, the overarching function of the weapon is to “Channel: Dumb Bomb,” or, move the munition from the aircraft carriage location to the ground target.  In this case, “channel” refers to movement from one location to another.

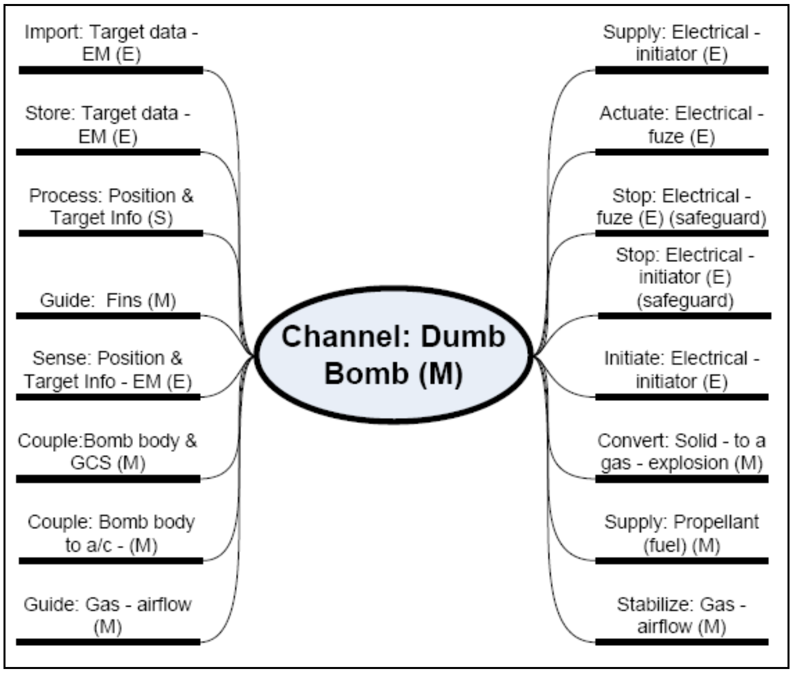
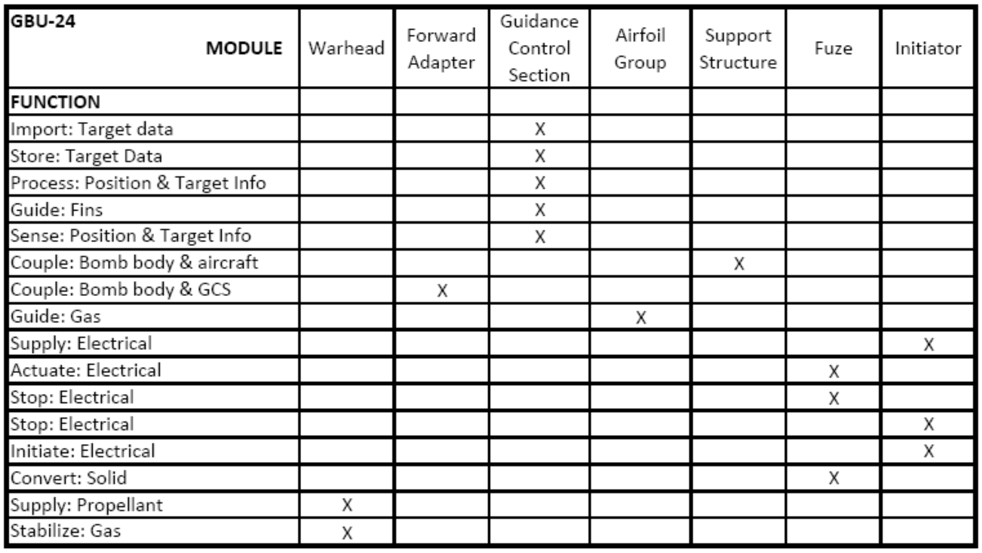


Figure 4.  GBU-24 Function Structure

The second step is to map the functions identified in the function structure from Figure 4 to modules as shown in Table 1. Module identification in the GBU-24 application was straight forward. In less modular designs, this may not be the case. It is important to note however, the identification of modules in a product is pivotal to three of the four contributing factors in the modularity vector (*V*, *X*, and ***Y***).

Table 1: GBU-24 function to module mapping



| **GBU-24**<br>**MODULE** | Warhead | Forward Adapter | Guidance Control Section | Airfoil Group | Support Structure | Fuze | Initiator |
|---|---|---|---|---|---|---|---|
| **FUNCTION** | | | | | | | |
| Import: Target data | | | X | | | | |
| Store: Target Data | | | X | | | | |
| Process: Position & Target Info | | | X | | | | |
| Guide: Fins | | | X | | | | |
| Sense: Position & Target Info | | | X | | | | |
| Couple: Bomb body & aircraft | | | | | X | | |
| Couple: Bomb body & GCS | | X | | | | | |
| Guide: Gas | | | | X | | | |
| Supply: Electrical | | | | | | | X |
| Actuate: Electrical | | | | | | X | |
| Stop: Electrical | | | | | | X | |
| Stop: Electrical | | | | | | | X |
| Initiate: Electrical | | | | | | | X |
| Convert: Solid | | | | | | X | |
| Supply: Propellant | X | | | | | | |
| Stabilize: Gas | X | | | | | | |

Once module identification was performed, Steps 3 and 4 of the analysis process could be accomplished either sequentially or in parallel. These two steps were chosen to be accomplished in parallel and the design structure matrix (DSM) was constructed with the GBU-24 modules as row and column labels. For this initial application and for simplification, a binary symmetric matrix was chosen that identifies only that an interface (by type) exists between two modules. After discounting the diagonal entries, the assessment of interfaces between the modules was made. These interfaces, along with the functional decomposition, were accomplished using SMEs and hands-on experience. The DSM/tensor for the GBU-24 is shown in Figure 5. Each horizontal layer of the tensor represents an interface type. Only half of the plot is shown for simplification since it is symmetrical. Each box represents an interface existence between the two modules identified in the row and column headings in the horizontal axes. The relationship between the modules, by interface type, is given in a typical DSM provide/depend association. Using the tensor plot, it is readily seen which interface types require more or less coupling for a given product.

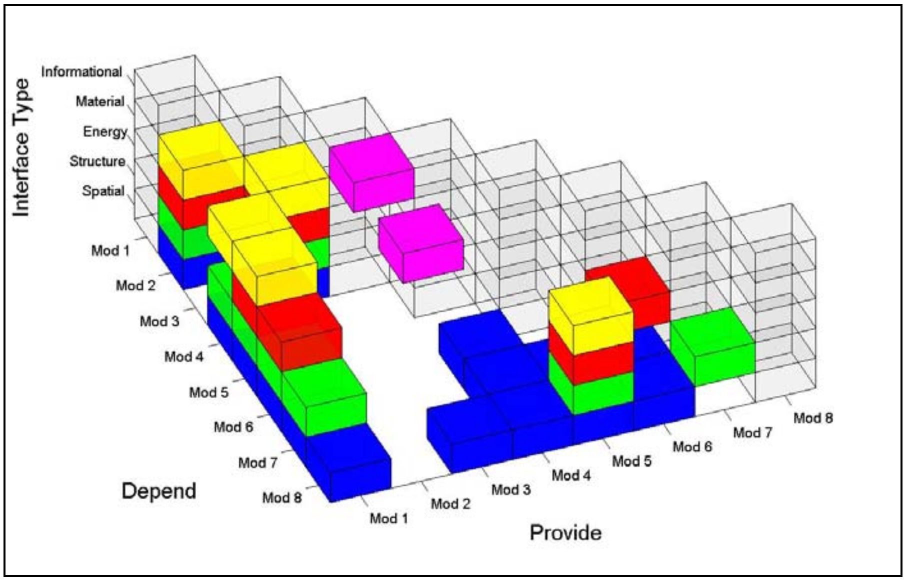


Figure 5. GBU-24 Tensor

After developing the GBU-24 tensor, the degree of coupling factor in the Vector Modularity Measure can be calculated. Using the eight modules identified in the DSMs/tensor plot, each module was categorized as unique or reused. After categorization, reusability was assessed. Continuing on with the reconfigurability assessment, a list of products was created for each module that is used in additional products beyond the GBU-24. The $S$, $t$, $r_{\text{act}}$, and $\sigma$ values were then calculated using the lists created for each module in the GBU-24 (see Stryker 2010 for the impact on the reconfigurability measure of using $r_{\text{act}}$ versus $r$ for the GBU-24). The values for these parameters, 19, 4, 84, and 2.36 respectively, led to the final calculation of the reconfigurability measure. Lastly, each of the functions identified for the product was summed in the $m$ value. While zero, one, or two fuze modules (and associated functions) can be used to build a complete GBU-24, it was assumed that the build would include one fuze module. The ability to use a second fuze module was considered as additional functionality. The additional functionality was captured in the $a$ parameter for extensibility. The equations for all of the modularity factors are summarized in Equations (9) and (10). The results for the GBU-24 modularity assessment are given in Equations (11) and (12).

$$VMM = \left[ \frac{\sum_{k=1}^{5} \left( \sum_{i=1}^{n} \sum_{j=1}^{n} DSMij_{i \neq j} \right)_k}{5n(n-1)},\ \frac{n_{mp}}{n},\ \boldsymbol{Y},\ \frac{a}{m} \right] \tag{9}$$

$$\boldsymbol{Y} = \left[ \begin{array}{cccc} \frac{r_{\text{act}}}{S} & \frac{r_{\text{act}}}{t} & \frac{t}{n} & \frac{r_{\text{act}}}{r_{\text{u.b.}}} \end{array} \right] \tag{10}$$

$$\boldsymbol{VMM}_{\textbf{GBU-24}} = \left[ 0.25,\ 0.63,\ \boldsymbol{Y}_{\textbf{GBU-24}},\ 0.06 \right] \tag{11}$$

$$\boldsymbol{Y}_{\textbf{GBU-24}} = \left[ \begin{array}{cccc} 4.42 & 21 & 0.5 & 0.17 \end{array} \right] \tag{12}$$

**GBU-31**. The analysis process for the GBU-31 was also accomplished and is summarized in the following steps and figures. This analysis process is summarized separately from the GBU-24 to outline the complete analysis process from start to finish. The $S$, $t$, $r_{\text{act}}$, and $\sigma$ values used for the GBU-31 were 17, 4, 33 and 4.5, respectively.

STEP 1: Figure 6.

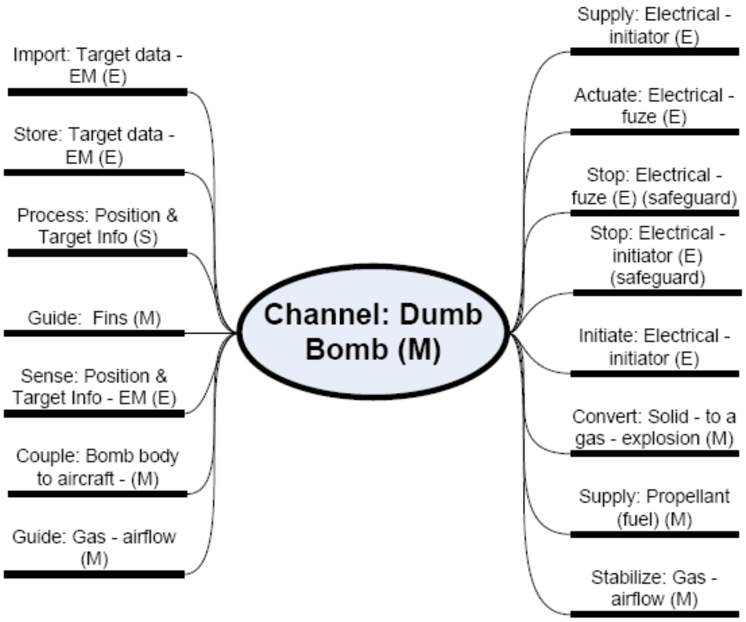


Figure 6. GBU-31 function structure

STEP 2: Table 2.

Table 2: GBU-31 function to module mapping

| **GBU-31**<br>**MODULE** | Warhead | Guidance Set | Proximity Sensor | Airfoil Group | Support Structure | Fuze | Initiator |
|---|---|---|---|---|---|---|---|
| **FUNCTION** | | | | | | | |
| Import: Target data | | X | | | | | |
| Store: Target Data | | X | | | | | |
| Process: Position & Target Info | | X | | | | | |
| Guide: Fins | | X | | | | | |
| Sense: Position & Target Info | | X | X | | | | |
| Couple: Bomb body & aircraft | | | | | X | | |
| Guide: Gas | | | | X | | | |
| Supply: Electrical | | | | | | | X |
| Actuate: Electrical | | | | | | X | |
| Stop: Electrical | | | | | | X | |
| Stop: Electrical | | | | | | | X |
| Initiate: Electrical | | | | | | | X |
| Convert: Solid | | | | | | X | |
| Supply: Propellant | X | | | | | | |
| Stabilize: Gas | | | | X | | | |

<u>STEPS 3 and 4</u>:  Figure 7.

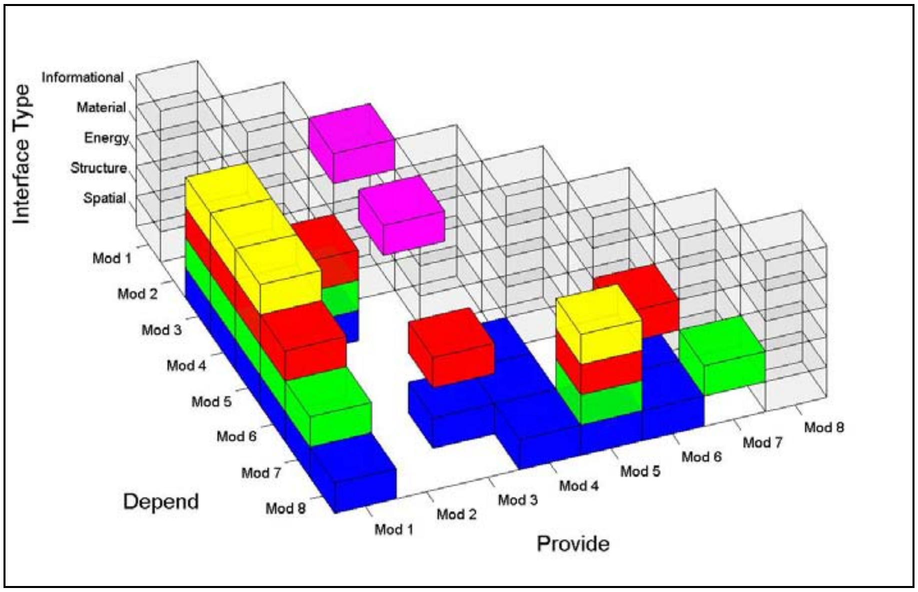


Figure 7.  GBU-31 Tensor

<u>STEP 5</u>:

$$\boldsymbol{VMM} = \left[ \frac{\sum_{k=1}^{5}\left(\sum_{i=1}^{n}\sum_{j=1}^{n} DSMij_{i\neq j}\right)_k}{5n(n-1)},\ \frac{n_{mp}}{n},\ \boldsymbol{Y},\ \frac{a}{m} \right] \tag{13}$$

$$\boldsymbol{Y} = \left[ \frac{r_{\mathrm{act}}}{S} \quad \frac{r_{\mathrm{act}}}{t} \quad \frac{t}{n} \quad \frac{r_{\mathrm{act}}}{r_{u.b.}} \right] \tag{14}$$

$$\boldsymbol{VMM}_{\mathbf{GBU\text{-}31}} = \left[0.26,\ 0.50,\ \boldsymbol{Y}_{\mathbf{GBU\text{-}31}},\ 0.00\right] \tag{15}$$

$$\boldsymbol{Y}_{\mathbf{GBU\text{-}31}} = \left[\ 1.94\ \ 8.25\ \ 0.5\ \ 0.10\ \right] \tag{16}$$

**Results**.  The results of the modularity assessment, including the reconfigurability measure, for the GBU-24 and GBU-31 precision guided munitions are shown in Equations (17) through (20).

$$\boldsymbol{VMM}_{\mathbf{GBU\text{-}24}} = \left[0.25,\ 0.63,\ \boldsymbol{Y}_{\mathbf{GBU\text{-}24}},\ 0.06\right] \tag{17}$$

$$\boldsymbol{VMM}_{\mathbf{GBU\text{-}31}} = \left[0.26,\ 0.50,\ \boldsymbol{Y}_{\mathbf{GBU\text{-}31}},\ 0.00\right] \tag{18}$$

$$\boldsymbol{Y}_{\mathbf{GBU\text{-}24}} = \left[\ 4.42\ \ 21\ \ 0.5\ \ 0.17\ \right] \tag{19}$$

$$\boldsymbol{Y}_{\mathbf{GBU\text{-}31}} = \left[\ 1.94\ \ 8.25\ \ 0.5\ \ 0.10\ \right] \tag{20}$$

Both PGMs perform the same overarching function, to guide or channel a bomb to a target on the ground.  Both munitions have similar function structures, modules, and interfaces.  This similarity is furthered characterized in the modularity assessment, specifically by the degree of coupling, $V$, and extensibility, $Z$, factors. Both factors show less than a 6% difference between the two PGMs. This small difference between the PGMs is the result of a two interface difference for $V$, and a one function difference in $Z$.

As mentioned previously, earlier modularity measures (Mikkola 2007, Hölttä-Otto 2007, Sosa 2007 etc.) focus on coupling of either design parameters or interfaces which is referred to as degree of coupling in this paper. Stopping at this point (assessing degree of coupling) in the assessment would yield an insignificant difference in the two products in terms of modularity and would result in the two designs being relatively equal in terms of modularity. The modularity measure equations given by Mikkola, Hölttä-Otto, and Sosa (Mikkola 2007, Hölttä-Otto 2007, Sosa 2007) were calculated for both PGM examples and in all three cases, the modularity measures indicated the same results as the Vector Modularity Measure introduced in this paper, that the GBU-24 is more modular than the GBU-31. While the analysis was consistent as to which munition is more modular, previous measures do not offer the additional insight into the specific benefits of modularity being realized by each munition.

Continuing the analysis process identified in this paper generates the next level of granularity in assessing the differences in modularity between the two PGMs. Specifically, the GBU-24 (Mk 84 variant) is identified as being more reusable and reconfigurable than the GBU-31 (Mk 84 variant). It is important to note that the Mk 84 variants of both munitions were used in the application in this research. The BLU-109 bomb body variant can also be used in both PGMs resulting in different modularity values and conclusions. While both munitions have similar modules, the GBU-24 has one module more than the GBU-31 that is reused in multiple products. The additional module results in the assessment identifying the GBU-24 as more reusable than the GBU-31. Neither weapon, however, is completely reusable ($n_{mp} < n$) from a modularity viewpoint.

The fuze -initiator constraints imposed on both GBUs as well as other pair-wise constraints hampered the total number of configurations achievable, $r$. Additionally for the GBU-31, the distribution of the $s_i$ terms achieves the minimum number of configurations possible for the given $S$ and $t$ pair. Since three out of the four ratios in $\boldsymbol{Y}$ uses $r$ in the reconfigurability factor, the result of the lower $r$ for the GBU-31 extended to the overall reconfigurability as rating lower than the GBU-24. While the analysis showed a small percentage difference between the two degree of coupling measures (less than 6%), this difference could be greater if non-realistic or non-achievable interfaces were eliminated. Ultimately, performing the analysis outlined in this paper identified differences in the two PGMs not previously realized when stopping the analysis after assessing the degree of coupling.

Finally, this analysis process can also be used when comparing the modularity of two designs of the same product or of a product that is being upgraded. Using the tensor plot, for example, modules that are highly coupled to each other and through which interface type(s) can be visualized. If the intentions of a designer or decision-maker are to increase modularity of a product, then the analysis can show contributing factors to the product's modularity and the benefits of increasing the modularity.

## Conclusions

Traditional modularity measures produce one real number, between zero and one, that can be used to compare relative modularity among multiple designs. Whereas these traditional modularity measures focus on coupling, whether between design parameters or interfaces among modules, the measure here builds upon that initial real number. The Vector Modularity Measure (VMM) presented captures not only the coupling attribute but also the reusability and flexibility attributes. The flexibility attribute is measured in terms of a product's ability to be adaptable to changing requirements which are specifically measures of reconfigurability and extensibility.

The VMM presented can be used to evaluate and compare multiple designs from a modularity viewpoint. Whether these designs are for similar products, the same product, or an upgrade of an existing product, the VMM presented here helps to illuminate various aspects of the product's modularity. This is especially helpful in highlighting where one product design is more modular than another as in the demonstrated case of the PGM. When comparing designs, the various benefits of modularity identified through the analysis process can be taken into account when making design decisions. It is hypothesized that the analysis process can also be used on conceptual designs as well as existing designs but was not attempted as part of this research.

Through the two PGM applications, it was demonstrated that while the two munitions are similar in function structures, modules, and interfaces, they are different in terms of reusability and reconfigurability. The particular modularity benefits of the GBU-24 over the GBU-31 were only highlighted once the analysis process presented in this paper was accomplished. If gaining the benefits of modularity is a design goal for a product, the VMM presented here helps to evaluate that design and highlight the benefits being realized.

Beyond measuring the four factors that make up the VMM, designers can use each equation of the calculations to determine where improvements to modularity can be made thus increasing the modularity benefits. For example, looking at Equation (7), a product with a lower $\sigma$ will in general result in a higher number of configurations, $r$, for a given product with the same $S$ and $t$ pair which will increase the reconfigurability of a product. Another example, using Equation (5), is to increase $n_{\mathrm{mp}}$ and hence $X$ by using modules in a product that have been used in other products.

Another use of this analysis is to refine the functional decomposition of a product. The second step in the analysis process maps modules to functions. This paper analyzed existing products and used reverse engineering to identify the modules and then map them to the corresponding functions they perform. The function to module mapping highlights where coupling exists between two or more modules. That is, two or more modules are necessary to accomplish one function. This information can then be used to reevaluate the functional decomposition or the module boundaries and hence the interfaces.

Two observations, based on the specific PGM application, are interesting and worthy of further investigation. The first observation is that the GBU-31 had a slightly higher degree of coupling that coincided with it being less reconfigurable than the GBU-24. Using this observation, a second observation is prompted in the form of a question. That is, does higher product complexity tend to discourage higher reconfigurability due to the number of interfaces, the types of interfaces, or a combination thereof?

The DSM/tensor in the degree of coupling factor, $V$, currently takes a binary approach. The next step, for future research, is to use directional information such that an interface can take on values of 0, 1, or 2 in the DSM/tensor for a given interface type. A “0” would represent no interface exists between two modules. A “1” would represent that a one-way directional interface exists. Lastly, a “2” would represent a bi-directional interface exists. Another future step in advancing the fidelity of this analysis process is to eliminate the non-realistic/non-achievable interfaces from the overall calculation in the $V$ factor. Currently, all matches between modules for each of the interface types are treated as realistic/achievable. Eliminating combinations of modules when calculating the number of reconfigurations would also advance the fidelity of this analysis process. The PGM application in this paper eliminated most, if not all, of the constrained reconfigurations but leaves the process of reconfiguration elimination to the analyst performing the Vector Modularity Measure assessment outlined herein.

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## Biography

Lt Col Amie Stryker is a recent graduate from the Air Force Institute of Technology where she earned her PhD in systems engineering. She holds a BS in aerospace engineering and MS in space studies. Her background includes work on several space transportation system missions, F-22 avionics developmental/operational testing, and spacecraft design for the German Aerospace Center, Oberpfaffenhoffen, Germany.

Dr. Dave Jacques is an Associate Professor of Aerospace Engineering at the Air Force Institute of Technology (AFIT). He holds a BS from Lehigh University, and an MS and PhD from AFIT. Dr. Jacques is a retired Air Force officer and currently chairs the Systems Engineering programs at AFIT where he served as the activation team chief for the Air Force Center for Systems Engineering in 2002 and 2003. His research interests include concept definition and evaluation, architecture evaluation, and optimal design of multi-agent systems and concepts.

Lt Col David Long is an instructor of engineering systems at the Air Force Institute of Technology. His research interests include system architecture, commonality, modularity, and unmanned aircraft systems.

## APPENDIX

Precision guided munition function definitions (from Figures 4 and 6) are listed in this appendix in operational terms. Each function-flow pairing follows the basic format given by Hirtz et al. (Hirtz 2002) and which is shown in a slightly modified format given in Equation (A1). In this format, the function is an action verb from the functional basis terminology, the flow is a noun, and in ( ) is the flow type. The three flow types are Material (M), Energy (E), and Signal (S).

Function : flow (flow type) (A1)

**Channel : Dumb bomb (M)** - Channel indicates movement from one location to another; it is used here to represent the movement of the munition from the aircraft to the target.

**Import : Target data - EM (E)** - Import is used to indicate or describe a flow entering the system boundary; target data is imported or downloaded from the aircraft to the munition guidance set.

**Store : Target data - EM (E)** - Store refers to the accumulation of a flow; target data is stored in memory in the munition guidance set for later use in munition guidance processing.

**Process : Position and target information (S)** - Process refers to submitting information to a treatment or method having a set number of operations or steps; the munition guidance set processes the position and target data or information to continually update the current position, desired position, overall flight path, control inputs, and fuzing timing.

**Guide : Fins (M)** - Guide is a secondary function (from channel) that indicates the direction of flow along a specific path; it is used here to indicate the reception of a control input from the guidance set that in turn provides an input to the mechanism to rotate the fins to achieve the desired flight path.

**Sense : Position and target information (E)** Sense is to perceive or become aware of a flow; it is used here in the traditional way of sensing an energy source, the laser return for the GBU-24 and the GPS signal for the GBU-31, that is used in determining relative position to the target.

**Couple : Bomb body to aircraft (M)** - Couple is a secondary function (from connect) that indicates joining or bringing together flows such that the members are still distinguishable from each other; the use of coupling is also used in the traditional way, here it represents the attachment or mating of the munition with the aircraft.

**Couple : Bomb body to GCS (M)** - Couple is a secondary function (from connect) that indicates joining or bringing together flows such that the members are still distinguishable from each other; the use of coupling is also used in the traditional way, here it represents the joining of the bomb body with the guidance control section.

**Guide : Gas - airflow (M)** - Guide is a secondary function (from channel) that indicates the direction of flow along a specific path; it is used here to indicate the guidance of the airflow around the actuators (e.g. fins) to achieve the desired flight path.

**Actuate : Electrical - fuze (E)** - Actuate refers to the commencing of energy, signal, or material in response to an imported control signal; it is used here to represent the commencing the electrical signal that will ignite the explosive material in the munition.

**Convert : Solid - to a gas - explosion (M)** - Convert is used to represent the conversion of one form of flow to another; the conversion used here is the explosive material or fuel that is ignited and converted into explosive energy.

**Stop : Electrical - fuze (E) (safeguard)** - Stop is a secondary function (from control magnitude) used to indicate the ceasing, preventing or transferring of a flow; it is used here to represent the prevention of inadvertent fuzing which is one of two safeguard mechanisms.

**Supply : Electrical - initiator (E)** - Supply is a secondary function (from provision) used to indicate the provision of a flow from storage; upon release of the munition, the initiator is activated and electrical energy is generated, stored and supplied to the fuze.

**Stop : Electrical - initiator (E) (safeguard)** - Stop is a secondary function (from control magnitude) used to indicate the ceasing, preventing or transferring of a flow; it is used here to represent the prevention of inadvertent charging of the initiator that would result in fuzing which is one of two safeguard mechanisms.

**Initiate : Electrical - initiator (E)** - Initiate is a secondary function (from control magnitude) that refers to the commencing of energy, signal, or material in response to an imported control signal; upon release of the munition, the initiator is activated and electrical energy is generated that is subsequently supplied to the fuze.

**Stabilize : Gas - airflow (M)** - Stabilize is a secondary function (from support) to indicate the prevention of a flow from changing course or location; the strakes are used to stabilize the airflow around the bomb body and to help guide the airflow towards the aft of the bomb body.

**Supply : Propellant - fuel (M)** - Supply is a secondary function (from provision) used to indicate the provision of a flow from storage; the explosive material is carried or housed within the bomb body.