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Executive Summary

This paper provides documentation, at a detailed mathematical level, of the portion of the Risk Assessment and Mitigation Framework for Strategic Materials (RAMF-SM) that calculates demands for strategic and critical materials.

RAMF-SM and its precursors have played a key role in the analyses that have supported the Reports to the Congress concerning requirements for the National Defense Stockpile (NDS) of strategic and critical non-fuel materials. The NDS was established in the World War II era and has been managed by the Department of Defense (DOD) since 1988. By law, DOD is required to submit periodic reports to Congress stating which materials, and in what amounts, the stockpile should contain.

RAMF-SM was developed by the Institute for Defense Analyses (IDA) as a suite of methodological tools and databases to aid in the assessment and determination of NDS contents. A major component of RAMF-SM is its "Step 2," the computation of material shortfalls in the context of a specified national emergency scenario. By law, this scenario must be consistent with DOD planning. Step 2 has three major substeps.

- Substep 2a determines the U.S. demands for goods and services that would occur in the scenario.
- Substep 2b determines the demands for materials, i.e., the amounts of materials that U.S. industry needs in order to produce output that will satisfy the demands computed in Substep 2a.
- Substep 2c determines the available supply of materials, taking into account the particular characteristics of the scenario as necessary. It then compares those supplies against the demands from Substep 2b and determines if there are any material shortfalls.

Subsequent steps of RAMF-SM examine ways to mitigate these shortfalls, including stockpiling.

This paper provides detailed documentation of Substep 2b. Two different algorithms to compute material demand are described. The more-commonly used one involves quantities called material consumption ratios, which are generally based on data from the Department of Commerce and the Department of the Interior. An alternative algorithm is used for materials with intensive defense demands.

Contents

1. Introduction

The intent of this paper is to provide documentation of the portion of the Risk Assessment and Mitigation Framework for Strategic Materials (RAMF-SM) that calculates demands for strategic and critical materials.

RAMF-SM and its precursors have played a key role in the analyses that have supported the biennial Reports to Congress concerning requirements for the National Defense Stockpile (NDS) of strategic and critical non-fuel materials.[1] RAMF-SM, which was developed by the Institute for Defense Analyses (IDA) and is discussed more fully in IDA Paper P-5190 (Thomason, et al., 2015) has six major steps:

1. Identify (and select for study) materials of concern to the U.S. national security community;
2. Compute material shortfalls, to assess whether significant problems could occur in a planning scenario (such as a national emergency scenario) to meet critical demands for materials with supplies likely to be available to the United States;
3. Assess the importance of overcoming (or the risks to the United States of not overcoming) those shortfalls through deliberate government mitigation actions;
4. Identify various promising government mitigation options to address any important shortfalls;
5. Assess and compare the specific costs and mitigation effects of these government mitigations options, both individually and together; and
6. Identify priorities among the materials for investments of taxpayer dollars, whether through stockpiling or other government investments, to mitigate important potential shortfalls.

Step 2 of RAMF-SM is concerned with determining shortfalls of materials in a specified planning scenario, typically a national emergency. Of interest here are its first three substeps:

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[1] The National Defense Stockpile was established in the World War II era and has been managed by the Department of Defense (DOD) since 1988. By law, DOD is required to submit periodic reports to Congress stating which materials, and in what amounts, the stockpile should contain. The most recent such report as of this writing is the *Strategic and Critical Materials 2015 Report on Stockpile Requirements* (U.S. Department of Defense, 2015), hereafter referred to as the 2015 Requirements Report.

- Substep 2a determines the U.S. demands for goods and services, and the corresponding demand for outputs from U.S. industry, that would occur in a certain specified national emergency. These demands are developed via economic modeling, with adjustments to model the specific characteristics of the national emergency scenario.[2] Demands are expressed in millions of constant-year dollars.
- Substep 2b determines the demands for materials, i.e., the amounts of materials that U.S. industry needs to produce output that will satisfy the demands computed in Substep 2a. The demands for materials are expressed in mass units (e.g., tons) of material, and are determined from the demands for goods and services through material consumption information, via the methodology discussed in this paper.
- Substep 2c accepts initial material supply levels and determines the available supply of materials, taking into account the characteristics of the particular national emergency scenario examined. It then compares those supplies with the material demands from substep 2b and computes material shortfalls. Material supplies and shortfalls are expressed in mass units of material.

A schematic interpretation of these substeps appears in Figure 1.

Several mathematical models and dozens of databases, encompassing thousands of data items, support the computations of these substeps. The modeling of substeps 2a and 2c has been well documented,[3] but that of substep 2b has not. Over the years various papers have discussed it, but in little detail. This paper comprehensively documents the computation of material demand in RAMF-SM, i.e., substep 2b.

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[2] A distinction must be made between demands and industrial output. Domestic demands for goods (and services) can be met either by items produced in the United States or by imported items. Therefore, satisfying some of the demand via imports leads to less demand for output from U.S. industry. However, goods produced in the United States for export constitute an additional demand for output from U.S. industry. The calculations of substep 2a estimate domestic demands for goods and services (defense, civilian, and emergency investment), exports, and imports. (These quantities are all expressed in "total requirements" terms, as discussed in Section 3.A.) Adding net exports (i.e., exports minus imports) to the domestic demands yields the demand for output from U.S. industry, which in turn leads to demand for materials. This addition is performed as part of substep 2b, but it could have been done in substep 2a instead.

[3] Substep 2a utilizes several different models. Two of these are economic forecasting models from the Inter-industry Forecasting Project at the University of Maryland (INFORUM). They are named LIFT (Long-term Inter-industry Forecasting Tool) (Meade, 2001) and ILIAD (Inter-industry Large-scale Integrated and Dynamic model) (Meade, 2011). Substep 2a also uses a model called FORCEMOB (Forces Mobilization Model) (Schwartz, 1996; also see Atwell, et al., 2015), which applies scenario-specific adjustments to the output of the economic models, computes industrial requirements to build weapons, and determines emergency investment demand. Substep 2c is modeled using the Stockpile Sizing Module (Santmire, 1997; also see Atwell, et al., 2014).

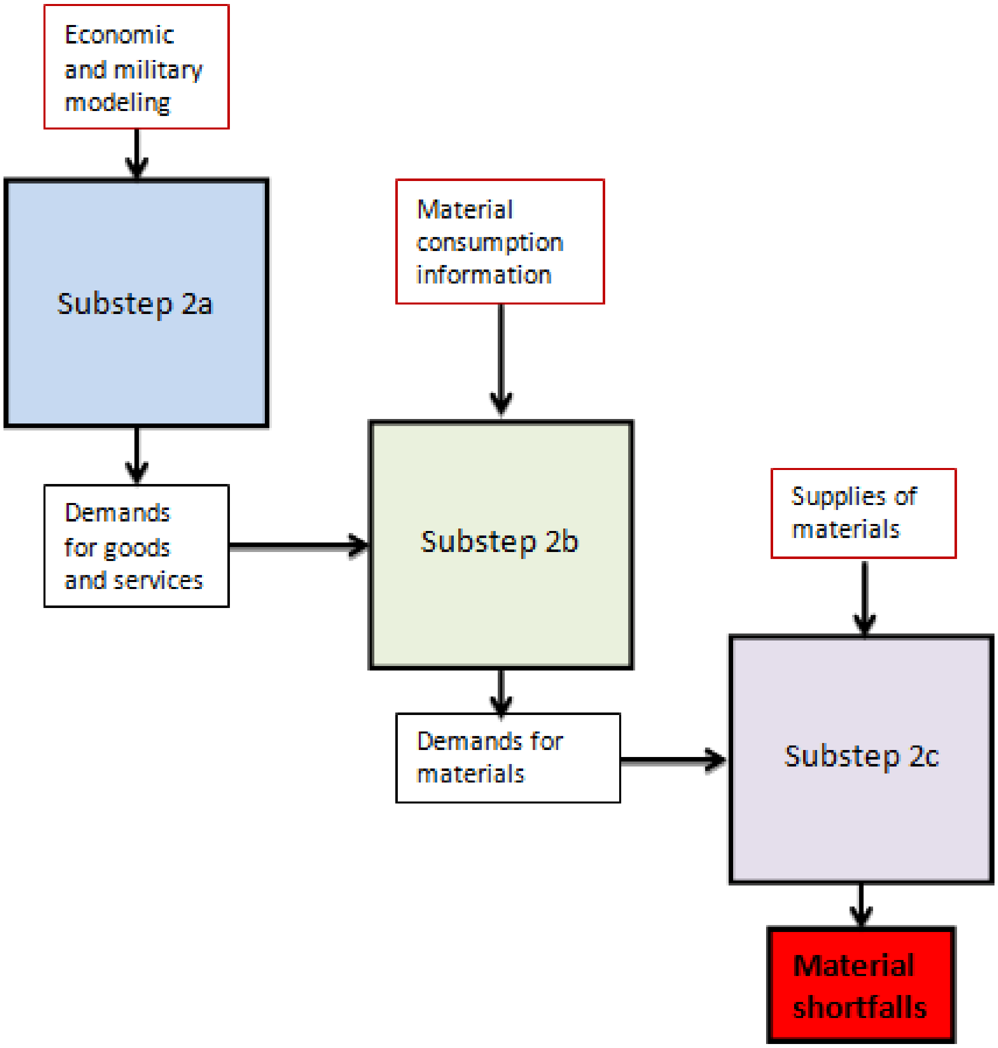

Figure 1. Interaction of Substeps 2a, 2b, and 2c of RAMF-SM

RAMF-SM uses two different algorithms for material demand computation. For most of the materials, the methodology makes use of quantities called material consumption ratios (MCRs). An MCR gives the amount of material (measured in mass units, such as tons) required for a given U.S. industry sector to produce a given dollar amount (generally, a billion dollars' worth) of its output.[4] The MCRs are computed based on information developed by the Department of Commerce (DOC) or the U.S. Geological Survey (USGS). The MCR methodology has been in place for many years.

[4] The industry sectors used are those of the ILIAD model. The current version of ILIAD models 360 different industry sectors, generally corresponding to the North American Industry Classification System (NAICS) 4-digit level.

One characteristic of the MCR methodology is that it apportions material demand between civilian and defense uses based on the underlying civilian/defense breakdown of the demands for goods and services (substep 2a). For specialized materials with intensive defense uses, the MCR method might underestimate the amount of material used for defense purposes. For such materials, an alternative demand computation methodology was developed that explicitly considers the proportion of material used in defense applications. The concept of such a methodology has been implemented in the modeling process for a long time, with some changes over the years. This paper describes the current version.

The remainder of this paper is structured as follows. Section 2 presents some background on the development of the material demand computation methodology. Section 3 documents the MCR methodology, and Section 4, the alternative demand computation methodology. Section 5 discusses the specific computer programs that RAMF-SM uses to implement the material demand calculations.

2. Background

The National Defense Stockpile has existed since the World War II era. In 1988, the Department of Defense assumed responsibility for managing it. The first Report to Congress on stockpile requirements prepared by DOD appeared in 1989. DOD tasked IDA to develop a methodology for determining the quantities of materials the stockpile should contain (Thomason, et al., 1990, 1993, 1996). Early IDA studies of the stockpile utilized a database of material consumption ratios that had been maintained by the Office of the Assistant Secretary of Defense (Program Analysis and Evaluation). But that database had not been updated since the mid-1980s. In 1992 a memorandum of understanding was signed with the Department of Commerce (DOC) to update the material consumption and application data (Thomason, et al., 1993; Tai, 1996), and DOC has continued to do so regularly. The particular version of the MCR computational methodology IDA used was developed by An-Jen Tai in the mid-1990s and has continued to be in use since then, with only minor formatting modifications (Tai and Thomason, 1999).

For "advanced" materials for which Commerce did not collect data, a number of special-purpose methods were used to determine material demand (Barnett, 1995a, 1995b). Most of those methods were similar enough to each other that they were formalized into a "proxy-MCR" methodology. Originally implemented on a spreadsheet, the proxy-MCR methodology was later turned into a computer program.[5] Eventually, it became apparent that for many of the non-Commerce materials, the actual MCR methodology (as opposed to some kind of proxy) was appropriate, and that sufficient data were available to support it. As the format of such data was not the same as that Commerce provided, a separate computer program was written to compute MCRs for those materials.

Although many materials previously modeled via the proxy-MCR methodology came to be modeled by the MCR methodology itself, the MCR methodology is not appropriate for materials with intensive defense uses, as stated earlier. Section 4 of this paper describes the particular version of the methodology—now referred to as the alternative demand computation program—that the 2015 Requirements Report used for determining demand for materials with intensive defense uses. The methodology might still undergo further development.

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[5] The best documentation of that version of the proxy-MCR program, which was used to support NDS Requirements Reports from 2001 through 2011, appears in Appendix C of IDA Paper P-4593 (Thomason, et al., 2010).

3. The Material Consumption Ratio Methodology

This section provides a mathematical description of the material consumption ratio methodology. It describes how the material consumption ratios (MCRs) are calculated and how they are used to compute material demand. Recall that an MCR gives the amount of material (measured in mass units, such as tons) that is required for a given U.S. industry sector to produce a billion dollars' worth of its output.

The MCR algorithm is a two-stage process. First, the MCRs are computed (see Sections 3.A and 3.B). Second, the MCRs are multiplied by the demands for industrial output (from substep 2a) and the results are added to yield overall material demands (see Section 3.D). Section 3.C verifies an important conservation property of the MCRs.

A. Input Data and Basic Terminology

The process is performed separately for each material. For now, assume that one particular material is under consideration.

A distinction is made between peacetime conditions and scenario conditions. The term peacetime is used to denote steady-state or business as usual, despite some possible ongoing general turmoil or inherent instability. The scenario conditions are those of the particular national emergency scenario to be analyzed. The term reference period denotes a recent year or set of years where historical data for material consumption and economic output are available. Quantities defined "in the reference period" refer to average annual amounts over the years in the reference period, under peacetime conditions. The scenario period is the time span of the national emergency scenario, which will generally start some years after the reference period, and might be several years long.

The process requires the following input data:

- Inputs concerning the material:
  - Amount of material (measured in mass units, such as tons) consumed by the United States in the reference period
  - List of application areas in which the material is used (in the United States)
  - Proportion of the consumption amount that is used in each given application area (in the reference period). The proportions must sum to 1.0.

  - For each application area, a list of industry sectors associated with that application area.
- Economic inputs (measured in millions of constant-year dollars):
  - For each industry sector:
    - Output of that sector in the reference period (under peacetime conditions)
    - For each year of the scenario, under the scenario conditions:
      - Defense demand, expressed in total requirements terms[6]
      - Civilian demand, expressed in total requirements terms
      - Exports, expressed in total requirements terms
      - Imports, expressed in total requirements terms
      - Emergency investment demand, expressed in total requirements terms[7]

The data on material consumption and applications have generally been obtained from material specialists at the Department of Commerce or the U.S. Geological Survey. The economic inputs are generated by the INFORUM models (LIFT, ILIAD) and FORCEMOB.[8] The link between the two sets of data is the lists of industry sectors associated with each application. These sectors are determined using the expert judgment of someone familiar with the industry sectors of the INFORUM models, with advice from the material specialists about the specific uses of the material in question.

This linking of material usage with industry sectors allows the construction of a modeling process that makes it possible to determine the change in demand for material that results from changes in the demand for output from a certain industry sector (as computed by the economic modeling).

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6 Total requirements demands include industrial output that goes to other industries, not just the output that goes to households, exports, or the government. See Miller and Blair, 1985, for an explanation of the concept. All of the demands for goods and services that are modeled by the FORCEMOB model and the demand computation algorithms are expressed in total requirements terms. The same concept applies to exports, i.e., goods produced in the U.S. for export. When applied to imports, total requirements encompass those U.S. industrial outputs that need not be produced because the demand that would give rise to those industrial outputs is instead satisfied by imported items.

7 The national emergency scenario might induce heavy demands on industry—more than peacetime industrial output can satisfy. FORCEMOB models the process of investing in new industrial productive capacity to meet that extra demand. But extra industrial output is needed to build that new productive capacity. That output is known as the emergency investment demand.

8 The INFORUM databases contain historical economic information, in addition to being used to predict the scenario information. The MCR creation process makes use of this historical information.

An example of applications and industry sectors might make some of the above concepts clearer. Imagine that a certain material is used 25% in switches and relays and 75% in optoelectronics. The switches and relays application is associated with three industries: 201–All other electronic components; 223–Relays and industrial controls; and 227–Wiring devices, where the industry numbers follow the sectoring scheme of the ILIAD model. The optoelectronics application is associated with two industries: 200–Semiconductors and electron tubes; and 201–All other electronic components. (It is possible for the same industry sector to be associated with more than one application area.) In practice, the data from the Department of Commerce provide the application areas and percentages, and give for each application area an associated group of NAICS codes, from which it is straightforward to determine the relevant ILIAD sectors.

B. Construction of the MCRs

The MCR represents the amount of material used by an industry sector in producing a billion dollars' worth of its output. Computations are performed using reference period values under peacetime conditions. The total amount of material consumed by industry is an input to the process. This material is apportioned among the industry sectors, by way of the application areas. The amount of material apportioned to (i.e., used by) a given industry sector is divided by the amount of that sector's output (in billions of dollars) to compute the MCR.

A mathematical description of the process is as follows. We start by assigning mathematical symbols to the input quantities listed above.

The reference period is indexed as time $t = 0$. The T years of the scenario period are indexed as $t = 1,\ldots,T$, even though the scenario might be posited as occurring some years after the reference period. Let j ($j = 1,\ldots,J$) index application area and i ($i = 1,\ldots,I$) index industry sector. Let

Γ = average annual amount of consumption of the material in the reference period,

φ_j = proportion of consumption used in application area j,

$\gamma_j = \Gamma\varphi_j$ = average annual amount of consumption of the material in application area j during the reference period,

δ_{ij} = 1 if industry sector i is associated with application area j, 0 if not, and

ω_{i0} = average annual output of industry sector i in the reference period (from the economic databases).

The following intermediate variables can be defined.

For each j, let S_j be the set of industry sectors associated with application area j, i.e., $S_j = \{i|\delta_{ij} = 1\}$.

Let $\Omega_j = \sum_{i \in S_j} \omega_{i0}$. This is the total amount of economic output of the industries associated with application area j in the reference period. It is clear that Ω_j is also equal to the quantity $\sum_{i=1}^{I} \delta_{ij} \omega_{i0}$.

Let $\psi_{ij} = \omega_{i0}/\Omega_j$ if industry sector i is associated with application area j, 0 if not. It is clear that $\psi_{ij} = \delta_{ij}\omega_{i0}/\Omega_j$, and that for each given j, $\sum_{i=1}^{I} \psi_{ij} = 1$.

The amount of material consumption in application area j can be apportioned among the industry sectors associated with that application area. Assume that this is done in proportion to the outputs of those sectors, i.e., the ω_{i0}. That is, the amount of material consumed in application area j associated with industry sector i can be estimated by $\psi_{ij}\gamma_j$. This value is zero for sectors not associated with application area j.

The total amount of material, call it Z_i, associated with industry sector i is then computed by summing over application area (j) the amount of material consumed in application area j that is associated with industry i.

In symbols

$$Z_i = \sum_{j=1}^{J} \gamma_j \, \psi_{ij}$$

i.e.,

$$Z_i = \sum_{j=1}^{J} \frac{\gamma_j \, \delta_{ij}\omega_{i0}}{\Omega_j}$$

or

$$Z_i = \omega_{i0} \sum_{j=1}^{J} \gamma_j \frac{\delta_{ij}}{\Omega_j}.$$

This is an amount of material consumption associated with industry sector i. The material consumption ratio is the ratio of this amount to the output of industry sector i. But the output is simply the variable ω_{i0}. Thus, the MCR, call it ρ_i, is defined by

$$\rho_i = \frac{Z_i}{\omega_{i0}} = \sum_{j=1}^{J} \gamma_j \, \frac{\delta_{ij}}{\Omega_j}.$$

C. Conservation Check with Peacetime Reference Period Demands

Suppose that demand data in the reference period under peacetime conditions were available. It would be satisfying to suppose that if the MCRs were applied to these data, the resultant computed material demand would equal the original material consumption amount. Under certain circumstances, this is true, as explained below.

Economic input-output theory (Miller and Blair, 1985), posits a fundamental identity that under peacetime conditions, the output of an industry sector should equal the "net demand sum," which is calculated as:

- defense demand for that sector's products
- plus civilian demand for that sector's products
- plus exports of that sector's products
- minus imports of that sector's products

(where all quantities are expressed in total requirements terms). Because INFORUM determines output and the demand components via different methodologies, the actual quantities in the INFORUM databases for output and net demand sum might differ from each other (this difference is referred to as statistical discrepancy). For purposes of constructing the MCRs, the net demand sum (in the reference period) is often used rather than the output itself. Letting d_{i0}, c_{i0}, x_{i0}, and m_{i0} denote the average annual defense demand, civilian demand, exports, and imports, respectively, in sector i during the reference period, and assuming that the values ω_{i0} used for the MCR construction satisfy the condition

$$\omega_{i0} = d_{i0} + c_{i0} + x_{i0} - m_{i0}\,,$$

then it can be verified algebraically that

$$\sum_{i=1}^{I} \rho_i \left(d_{i0} + c_{i0} + x_{i0} - m_{i0}\right)$$

is equal to Γ, the total (average annual) consumption of the material during the reference period. [9]

The proof of this is straightforward. The indicated sum is equal to

[9] As a check on the accuracy of the computer programs, this kind of calculation has, in fact, been performed with the actual data.

$$\sum_{i=1}^{I} \rho_i \ \omega_{i0}$$

Let Q be used as symbol for this sum. Recall that ρ_i is defined as Z_i/ω_{i0}, where

$$Z_i = \sum_{j=1}^{J} \frac{\gamma_j \ \delta_{ij} \ \omega_{i0}}{\Omega_j}.$$

Thus, $\rho_i \ \omega_{i0} = Z_i$ and

$$Q = \sum_{i=1}^{I} \rho_i \ \omega_{i0} = \sum_{i=1}^{I} Z_i = \sum_{i=1}^{I} \sum_{j=1}^{J} \frac{\gamma_j \ \delta_{ij} \ \omega_{i0}}{\Omega_j}.$$

Interchanging the order of summation, we get

$$Q = \sum_{j=1}^{J} \sum_{i=1}^{I} \frac{\gamma_j \ \delta_{ij} \ \omega_{i0}}{\Omega_j}$$

or

$$Q = \sum_{j=1}^{J} \frac{\gamma_j}{\Omega_j} \left(\sum_{i=1}^{I} \delta_{ij} \omega_{i0} \right).$$

But recall that Ω_j is defined as $\Omega_j = \sum_{i=1}^{I} \delta_{ij} \ \omega_{i0}$, so Q becomes $\sum_{j=1}^{J} \gamma_j$, or Γ. ▮

D. Computation of Material Demands in the Scenario Period

We now turn from the reference period and peacetime conditions to the scenario period and scenario (national emergency) conditions. The economic modeling has computed, for each industry sector *i* and each year *t* of the scenario period,

- d'_{it} = defense demand for the products of sector *i* in year *t* under scenario conditions (might be higher than peacetime because of weapon and munitions requirements)
- c'_{it}= civilian demand for the products of sector *i* in year *t* under scenario conditions (might be lower than peacetime because nonessential demand is excluded)
- v'_{it}= emergency investment demand for the products of sector *i* in year *t* under scenario conditions (not relevant, and set to zero under peacetime conditions)

- x'_{it}= exports of the products of sector i in year t under scenario conditions (might be different from peacetime because of policy decisions)
- m'_{it}= imports of the products of sector i in year t under scenario conditions (might be lower than peacetime because of unreliability of supplier countries)

Each of these components is multiplied by the MCR ρ_i to yield an amount of material associated with that combination of component, year, and industry sector.[10] Net exports are then amalgamated with civilian demand, so that the computer program reports the civilian demand as $\rho_i(c'_{it} + x'_{it} - m'_{it})$.[11] The defense demand is $\rho_i d'_{it}$ and the emergency investment demand is $\rho_i v'_{it}$. The values for each component are then summed over all industry sectors (i) to yield overall demands for the material that are associated with each component, in the given year.[12]

These computations are implemented by a computer program known as the Requirements Creation Submodule. The overall material demands, by material, component, and year, are written to a file, which later becomes an input to the Stockpile Sizing Module. The program also generates two more detailed output files. One of them contains material demand by industry sector, component, and year, for the 20 industries with the highest demand. The other detailed output file contains material demand by industry sector and component (summed over the years of the scenario). The program could be modified as desired to generate additional output files.

E. Collection of Scenario Demands by Application Area

The MCRs are a function of industry sector, not application area, and the resultant material demands are computed industry sector by industry sector, not application area by application area. It is possible, however, to compute a demand for the material in each application area. This information is useful when examining the effect of substitution possibilities, which can be different for different application areas.

Demands by application area can be estimated via the following process. As indicated in Section 3.B, the computation of the MCRs involves quantities denoted $\gamma_j \psi_{ij}$, the amount

[10] Technically, the components are expressed in millions of dollars. Before the MCR is applied, the components are converted to billions of dollars, to be compatible with the units of the MCRs. But the notation above should be clear.

[11] Occasionally, this quantity is negative; if so, zero is used instead. Adding in net exports has the effect of converting demands to industrial output requirements, as discussed in Section 1.

[12] At times, it is useful to distinguish quantities d_{it}, c_{it}, x_{it}, and m_{it}, which represent defense demands, civilian demands, exports, and imports, respectively, on industry sector i in year t of the scenario but under peacetime, rather than national emergency, conditions. The MCRs can be (and are) applied to these quantities to yield peacetime material demands in the scenario period.

of material consumed in application j that is associated with industry sector i. The quantity Z_i, computed as

$$Z_i = \sum_{j=1}^{J} \gamma_j \, \psi_{ij} \, ,$$

represents the average annual consumption of the material by industry i during the reference period. The ratio $\gamma_j \psi_{ij} / Z_i$ can be regarded as the proportion of consumption by industry i that is associated with application area j. These ratios can then be multiplied by any of the scenario consumption components $\rho_i d'_{it}$, $\rho_i(c'_{it} + x'_{it} - m'_{it})$, and the like, to get amounts of material demand in the indicated component in industry i that are associated with application area j. For each j, these amounts can then be summed over industry sector to get material demand amounts, in the indicated component, associated with application area j.

A “demand by application” computer program has been written to perform this calculation. The program needs access to the $\gamma_j \psi_{ij} / Z_i$, which are intermediate quantities in the MCR creation process. The MCR creation program writes these quantities to a file. The demand by application program:

1. reads this file;
2. reads the material demand file (by industry sector, material, and component) created by the Requirements Creation Submodule for the particular (national emergency) scenario under consideration;
3. applies the $\gamma_j \psi_{ij} / Z_i$ ratios to the each material demand quantity indicated above to get a quantity associated with an application area; and
4. computes sums over industries for each application area.

In the current version of the program, the resultant demands vary by application area and component, but not time period (i.e., year). Modifications could be made to compute the demand by time period too.

4. The Alternative Demand Computation Methodology

A. Introduction

The MCR methodology is consistent with a tacit assumption that material usage is apportioned between civilian and defense uses in accordance with the underlying economic demand data for the corresponding industry sectors. In general, civilian economic demands are considerably larger than defense ones. For some highly specialized materials with intensive military use, the MCR methodology would underestimate defense usage. For these materials, an alternative methodology was developed, in which subject matter experts specify a fraction of military use for each material application. These explicit military proportions allow the projected military and civilian material demands to be consistent with actual usage patterns.

In some form, this methodology has been in use since at least the mid-1990s, as discussed in Section 2. This paper documents the version that was used to support the 2015 Requirements Report. But the methodology and its associated computer program might change in the future.

B. General Description

Recall that the MCR methodology is a two-stage process: first, the MCRs are computed; then they are multiplied by the demands for goods and services (from FORCEMOB) to compute demands for materials. In contrast, the alternative demand computation methodology computes the material demands directly, incorporating elements of both stages of the MCR methodology while explicitly considering defense usage.

Let the terminology and mathematical notation be the same as in Section 3. The process is performed separately for each material; assume for now that one particular material is under consideration. The procedure starts with the average annual amount of consumption of the material in the reference period. The material is used in a number of application areas, each of which is associated with a number of different industry (ILIAD) sectors. For each application area, the proportion of overall material consumption associated with the application area is given. The alternative demand computation algorithm also specifies for each application area the proportion of its material use that is for defense purposes (the remainder is for civilian uses). Therefore for each application area, amounts of defense consumption and amounts of civilian consumption of the material in the reference period are computed.

Two FORCEMOB runs are used. The first run is the one associated with the particular national emergency scenario being modeled. The second one has peacetime assumptions and encompasses all years from the beginning of the reference period through the end of the scenario period. Consider a given application area. Based on the FORCEMOB output (i.e., economic demands) for the industry sectors associated with the application area, four different factors are computed for each year of the scenario period:

- Defense growth factor
- Civilian growth factor
- Defense scenario adjustment factor
- Civilian scenario adjustment factor.

The growth factors account for differences in demand between the reference period and the given scenario year (generally due to economic growth). The scenario adjustment factors account for differences between emergency scenario conditions and peacetime conditions. (For example, defense demands might be greater than in peacetime because of weapon and munition regeneration requirements, while civilian demands might be less than in peacetime because only essential civilian demand is included.)

The defense demand in a given scenario year in a given application area is computed by taking the defense consumption in that application area in the reference period and multiplying it by the defense growth factor and the defense scenario adjustment factor. The corresponding computation is made for civilian demand. The demands in the various application areas are summed to yield overall defense and civilian demands for each scenario year.

C. Mathematical Description

The above description can be formalized mathematically as follows. Assume that one specific material is under consideration. Let the notation of Section 3 still hold, and in addition, let μ_j be the proportion of demand in application area j that is used for defense purposes in the reference period. The quantity μ_j is an input to the process that can vary by application area.

The overall material consumption amount in the reference period, Γ, is partitioned into amounts γ_j, the amount of material consumed in application area j, and the amount γ_j is subdivided into an amount $\mu_j\gamma_j$ associated with defense uses and an amount $(1-\mu_j)\gamma_j$ associated with civilian uses.

Recall that d_{it}, c_{it}, x_{it}, and m_{it} indicate the defense demand, civilian demand, exports, and imports, expressed in total requirements terms, in industry sector i in year t, under peacetime conditions. The index t=0 denotes the reference period (average annual demands) and t=1,…,T denote the years of the scenario period. The quantity δ_{ij} is 1 if industry sector i is associated with application area j, zero if not. Quantities d'_{it}, c'_{it}, v'_{it}, x'_{it}, and m'_{it} indicate the defense demand, civilian demand, emergency investment demand, exports, and imports, respectively, expressed in total requirements terms, in industry sector i in year t (t=1,…,T) under the scenario conditions. For each application area, collect the defense and civilian demands for goods and services for the industries associated with that application area, as follows. Let

> $U_{jt} = \sum_{i=1}^{I} \delta_{ij} d_{it}$ t=0,…,T, the defense demand for goods and services in application area j in year t under peacetime conditions.
>
> $V_{jt} = \sum_{i=1}^{I} \delta_{ij}(c_{it} + x_{it} - m_{it})$ t=0,…,T, the civilian demand plus net exports for goods and services in application area j in year t under peacetime conditions.
>
> $U'_{jt} = \sum_{i=1}^{I} \delta_{ij}(d'_{it} + v'_{it})$ t=1,…,T, the defense plus emergency investment demand for goods and services in application area j in year t under emergency scenario conditions. Emergency investment demand is added in with defense demand (see discussion below).
>
> $V'_{jt} = \sum_{i=1}^{I} \delta_{ij}(c'_{it} + x'_{it} - m'_{it})$ t=1,…,T, the civilian demand plus net exports for goods and services in application area j in year t under emergency scenario conditions.

Note that net exports are added to the civilian demand, as in the MCR algorithm. Also, emergency investment demand is added to the defense demand. The rationale for this is discussed later in this section.

Define the defense growth factor in application area j in year t (for t=1,…,T) as U_{jt}/U_{j0}, the civilian growth factor as V_{jt}/V_{j0}, the defense scenario adjustment factor as U'_{jt}/U_{jt}, and the civilian scenario adjustment factor as V'_{jt}/V_{jt}. The defense demand in application area j in year t under emergency scenario conditions—call it D'_{jt}—is the product of the defense consumption in the reference period, the defense growth factor, and the defense scenario adjustment factor, i.e.,

$$D'_{jt} = \mu_j \gamma_j (U_{jt}/U_{j0})(U'_{jt}/U_{jt}).$$

The terms U_{jt} cancel each other, so one can write

$$D'_{jt} = \mu_j \gamma_j (U'_{jt}/U_{j0}).$$

Similarly, the civilian demand in application area j in year t under emergency scenario conditions is the product of the civilian consumption in the reference period, the civilian growth factor, and the civilian adjustment factor, i.e.,

$$C'_{jt} = (1-\mu_j)\gamma_j (V_{jt}/V_{j0})(V'_{jt}/V_{jt}) = (1-\mu_j)\gamma_j (V'_{jt}/V_{j0}).$$

The overall defense demand for the material in year t under emergency scenario conditions is the sum over all application areas j of the D'_{jt}

$$D_t^{\text{tot}} = \sum_{j=1}^{J} D'_{jt}.$$

Similarly, the overall civilian demand material in year t under emergency scenario conditions is the sum over all application areas j of the C'_{jt} :

$$C_t^{\text{tot}} = \sum_{j=1}^{J} C'_{jt}.$$

These quantities constitute the main output of the material demand computation process. They are input to the Stockpile Sizing Module, which implements substep 2c of RAMF-SM.

The alternative demand computation algorithm does not compute an explicit emergency investment demand amount for materials, but the emergency investment demands on industry are added to the defense demands when forming the scenario adjustment factor. Modeling the emergency investment demands in the alternative demand computation procedure has always been somewhat problematic. Until recently, they were not taken into account at all. Fortunately, they tend to be very small in comparison to the defense and civilian demands. The current treatment, while admittedly a heuristic, does at least account for them. Modeling emergency investment demands in a less heuristic manner is an area for improvement in the modeling process.

An interesting property of the alternative demand computation procedure is as follows. Suppose that:

- instead of being a fixed quantity μ_j, the defense fraction of material use in an application area is computed from the relative proportions of defense and civilian peacetime economic demands for the industry sectors associated for that application, varying by scenario year;
- the average annual net demand sum (defense demand plus civilian demand plus exports minus imports, where all components are expressed in total requirements terms) in the reference period of the peacetime FORCEMOB run is the same as the quantity ω_{i0} used in the MCR computation, for all industry sectors i; and
- the national emergency scenario does not have any emergency investment demand for goods and services.

Then it can be shown that the MCR method and the alternative demand computation method produce the same overall total defense and civilian material demands.

D. Computation of Material Demands by Industry Sector

The MCR algorithm computes material demands by industry sector (an MCR applies to a single industry sector). An auxiliary program can then aggregate them by application area (see Section 3.E). In contrast, the alternative demand computation algorithm computes the material demands by application area. It is not unreasonable to apportion demand in an application area among the industries associated with that application area, in proportion to the demands on those industries. For informative purposes, a section of the computer program performs such a procedure, adds up the associated demands by industry, and outputs a report.

5. Description of Associated Computer Programs

Currently, four different computer programs are used to implement the calculations associated with the determination of material demand in RAMF-SM Step 2.

1. MCR creation program for Commerce materials. The material consumption and application information furnished by the Department of Commerce is structured in a very specific format. The MCR creation program is consistent with this format. It takes the Commerce information, along with historical information from the economic databases, and computes MCRs.
2. MCR creation program for non-Commerce materials. This program performs the same kinds of calculations as the program above, but the format of the inputs is different.
3. Requirements Creation Submodule. This program multiplies the MCRs by the demands for goods and services (more precisely, demands for industrial output) to obtain demands for materials. Originally part of the Stockpile Sizing Module, it was broken off into a separate, stand-alone program.[13]
4. Alternative demand computation program. This program implements the alternative demand computation algorithm, as described in Section 4.

These programs were intended for internal use, rather than as products for public release. Some have portions of code that were used in the past but not currently. Some of them are changed often. The alternative demand computation algorithm is constantly being refined. Other programs are changed to be consistent with new forms and formats of the input data. Some of the programs might be rewritten in different computer languages soon.

Documentation of the programs is sketchy. Given that the programs are—at least, as of now—frequently changed, writing detailed documentation of them at this point is probably a misuse of resources. As partial interim documentation, this section describes the structure of the major data input files associated with each program and the specific kinds of data inputs they contain. Many of these files are tab-delimited text files, which

[13] The Stockpile Sizing Module documentation from 1997 (Santmire, 1997) contains documentation of the Requirements Creation Submodule that is still fairly current. But the documentation contains some inaccuracies, and some of the features available in the submodule are not being used now.

can be (and have been) prepared in Excel and saved in text format. These files are likely to retain their structure and inputs, even if the underlying computer programs are rewritten.

In addition to the data input files, each program has a "control inputs file" that contains the names of the data input files, overall parameters such as scenario dates, and a place for user comments. As the structure of the control inputs files might be subject to change, they are not described in detail here.

A. Major Data Input Files for the Commerce MCR Creation Program

Table 1 shows the major data input files to the Commerce MCR Creation Program, listing the specific fields of information that appear on each data line. The control inputs file for this program also contains information not usually found in a control inputs file. In addition to year span and data file name information, it contains, for each material under consideration, its short name to be used in the Stockpile Sizing Module database, an index number for the units of measure the consumption data are expressed in, and an index number for the units of measure to be used by the Stockpile Sizing Module. These index numbers are keyed to the Units of Measure file. The materials must be listed in the same order as in the Material Consumption and Application File.

Table 1. Input Data Files for the Commerce MCR Creation Program

Material Consumption and Application File	
	Each section of the file has a header line with the material number, material name, and units of measure.
	Then a list of records follows that contains the application and consumption information, with the following fields. (The historical year span must fit into the overall year span.)
1	List of group of associated NAICS codes
2	Application name/description
3	Mnemonic name for NAICS group
4	U.S. consumption amount for first overall year
5	U.S. consumption amount for second overall year
…	…
n	U.S. consumption amount for last overall year
NAICS Group Information File	
1	Mnemonic name for NAICS group
2	Number of associated industry (ILIAD) sectors
3	Position in NAICS Group Associated Industries File of first associated ILIAD sector
NAICS Group Associated Industries File	
1	Mnemonic name for NAICS group
2	Index number (i=1, 2, 3,...) of ILIAD sector associated with that NAICS group
3	ILIAD sector number of i-th ILIAD sector associated with that NAICS group
Units of Measure File (space-delimited)	
	Top line showing number of entries. Then a section with the following fields.
1	Index number (1, 2, 3...)
2	Name of unit of measure, encased in single quotes
3	Number of pounds in this unit of measure
Economic Output File	
1	Industry (ILIAD) sector number
2	U.S. output or net demand sum (in that sector) for first historical year
3	U.S. output or net demand sum for second historical year
…	…
h	U.S. output or net demand sum for last historical year
Control Inputs File Material Information	
	Short material name
	Index number for units of measure for Commerce data
	Index number for units of measure for Requirements Report study

B. Major Data Input Files for the Non-Commerce Materials MCR Creation Program

Table 2 shows the major input files to the Non-Commerce Materials MCR Creation Program, listing the specific fields of information that appear on each data line.

Table 2. Input Data Files for the Non-Commerce MCR Creation Program

Material Consumption File (Year span for each material must fit into the overall year span.)	
1	Material short name
2	Material long name (more descriptive)
3	Units of measure
4	U.S. consumption amount for first overall year
5	U.S. consumption amount for second overall year
…	…
n	U.S. consumption amount for last overall year
Industrial Output File (Year span for each material must fit into the industrial output year span.)	
1	ILIAD sector number
2	U.S. output or net demand sum (in that sector) for first year of industrial output year span
3	U.S. output or net demand sum for second year of industrial output year span
…	…
r	U.S. output or net demand sum for last year of industrial output year span
Material Application Areas File	
1	Material short name
2	Application area number (1, 2, 3,…)
3	Application area name
4	Proportion of use
5	Number of associated industry sectors
6	Sector number (ILIAD) of first associated industry sector
Application by Industry File	
1	Material short name
2	Application area number
3	Order number (j=1, 2, 3,…)
4	Sector number (ILIAD) of j-th associated industry sector
Material Year Spans File	
1	Material short name
2	Starting year of reference period for that material
3	Ending year of reference period for that material

C. Major Data Input Files for the Requirements Creation Submodule

The Requirements Creation Submodule multiplies the MCRs by the industry demands (from FORCEMOB) to determine demands for materials. Originally part of the Stockpile Sizing Module (Santmire, 1997) it was converted to a separate, stand-alone program. The program has some optional features such as inflation conversion, units of measure conversion, and grouping of materials, but these have not been tested in a long time and their use is not recommended. The file guide below shows an input format that does not necessitate their use. The MCRs resulting from the two different MCR creation programs are usually amalgamated into one file for input to the Requirements Creation Submodule.[14] The program will attempt to compute demands for every material listed in the material names and information file.

Table 3 shows the major input files to the Requirements Creation Submodule, listing the specific fields of information that appear on each data line.

Table 3. Input Data Files for the Requirements Creation Submodule

FORCEMOB output for scenario under consideration (prepared by FORCEMOB program)	
Material Consumption Ratios (MCRs) File	
1	Industry sector number (ILIAD)
2	Material short name
3	MCR value
Material Names and Information File	
	The following simplified information is recommended for now.
1	Order number (1, 2, 3,…)
2	Material short name
3	Units of measure
4	Units of measure (repeated)
5	the number 1
6	the number 1 (repeated)
Inflation/Conversion Factors File	
1	Industry sector number (ILIAD)
2	Inflation or conversion factor (often 0.001, to convert $M to $B)

[14] At this point, some editing is usually done in Excel to delete leading and trailing spaces from material names, to sort the file by material name and then industry sector number, and to apply special factors to convert contained metal to gross weight for selected materials. The resultant MCR file is then saved as a tab-delimited text file.

D. Major Data Input Files for the Alternative Demand Computation Program

Table 4 shows the structure of the input files to the Alternative Demand Computation Program, listing the specific fields of information that appear on each data line.

Table 4. Input Data Files for the Alternative Demand Computation Program

List of Industry Sectors and their Names (Program is set up to read the Element input file for FORCEMOB.)	
Material Consumption File (Year span for each material must fit into the overall year span.)	
1	Material short name
2	Material long name (more descriptive)
3	Units of measure
4	U.S. consumption amount for first overall year
5	U.S. consumption amount for second overall year
…	…
n	U.S. consumption amount for last overall year
Defense Usage Fractions File	
1	Material short name
2	Application area number
3	The word "MILFRAC"
4	Proportion of material use in the application area that is for defense purposes
Material Application Areas File	
1	Material short name
2	Application area number (1, 2, 3,…)
3	Application area name
4	Proportion of overall U.S. consumption used in that application area
5	Number of associated industry sectors
6	Sector number (ILIAD) of first associated industry sector
Application by Industry File	
1	Material short name
2	Application area number
3	Order number (j=1, 2, 3,…)
4	Sector number (ILIAD) of j-th associated industry sector for that application
Material Year Spans File	
1	Material short name
2	Starting year of reference period for that material
3	Ending year of reference period for that material
FORCEMOB output for peacetime scenario (prepared by FORCEMOB program)	
FORCEMOB output for emergency scenario (prepared by FORCEMOB program)	

Appendix A
Illustrations

Figure

Tables

Appendix B
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Appendix C
Abbreviations

DOC	Department of Commerce
DOD	Department of Defense
FORCEMOB	Forces Mobilization Model
IDA	Institute for Defense Analyses
ILIAD	Interindustry Large-scale Integrated and Dynamic Model
INFORUM	Interindustry Forecasting Project at the University of Maryland
LIFT	Long-term Interindustry Forecasting Tool
MCRs	Material Consumption Ratios
MILFRAC	Military Fraction
NAICS	North American Industry Classification System
NDS	National Defense Stockpile
RAMF-SM	Risk Assessment and Mitigation Framework for Strategic Materials
USGS	U.S. Geological Survey

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14. ABSTRACT

This paper provides documentation, at a detailed mathematical level, of the portion of the Risk Assessment and Mitigation Framework for Strategic Materials (RAMF-SM) that calculates demands for strategic and critical materials. Two different algorithms to compute material demand are described. The more commonly used one involves quantities called material consumption ratios, which are generally based on data from the Department of Commerce and the Department of the Interior. An alternative algorithm is used for materials with intensive defense demands. Developed by the Institute for Defense Analyses, RAMF-SM has played a key role in the analyses that have supported the Reports to the Congress from the Department of Defense concerning requirements for the National Defense Stockpile of strategic and critical non-fuel materials.

15. SUBJECT TERMS

strategic materials, critical materials, National Defense Stockpile, Defense Logistics Agency, methodology, material consumption

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