A Structured Design & Analysis Methodology for Guided Weapon Concepts

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Abstract

Formulating and analyzing guided weapon concepts to meet user needs is both an art and a science. Choices made for certain subsystems impact the selection and design of other subsystems, dictating the need for an integrated approach. It is clear that the sequence and method used for model development or modification must be carefully chosen to account for subsystem interaction in order to minimize subsystem model redesign. Additionally, optimal choice of simulation runs is important during the concept formulation phase as well as during the final evaluation phase for weapon concept comparisons to best aid the selection and adjustment of design parameters.

A methodology has been developed for guided weapon concept formulation, modeling, and analysis. The perspective is from the standpoint of a government laboratory that is developing new guided munition technology. The focus is not on detailed weapon design, but rather on high-level concept design, that allows comparison and selection of one or more concepts for a more detailed design later. The methodology addresses the functional interaction of all weapon subsystems and follows a sequential design. The result is a non-optimal, but highly useful solution, which looks at concept viability. The methodology also addresses simulation-generated data used in the design process and in the ultimate analysis process to compare performance with user requirements.

1. Introduction

At the Air Force Research Laboratory's Munitions Directorate, located at Eglin AFB, Florida, the Guidance Simulation Branch of the Advanced Guidance Division (AFRL/MNGG) is responsible for analyzing the effect of evolving laboratory technologies on the performance of existing and conceptual air-launched guided munitions. Simulation development at AFRL/MNGG is accomplished using the recently developed MSTARS (Munition Simulation Tools and Resources) Simulation System[1], a

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[1] For more information on MSTARS, contact Mr. Scott Hess at (850) 882-8195 ext. 3282 or hessjs@eglin.af.mil.

visual simulation environment, which contains a repository of munition component models. The visual environment and the repository perfectly suit the needs of AFRL/MNGG because they enable simulations to be developed rapidly based on prototype system components that can be modified as needed to meet customer requirements. Additionally, the visual environment provides an intuitive feel of how the simulation components work together. Figure 1 shows the user interface presented at the MSTARS munition diagram level.
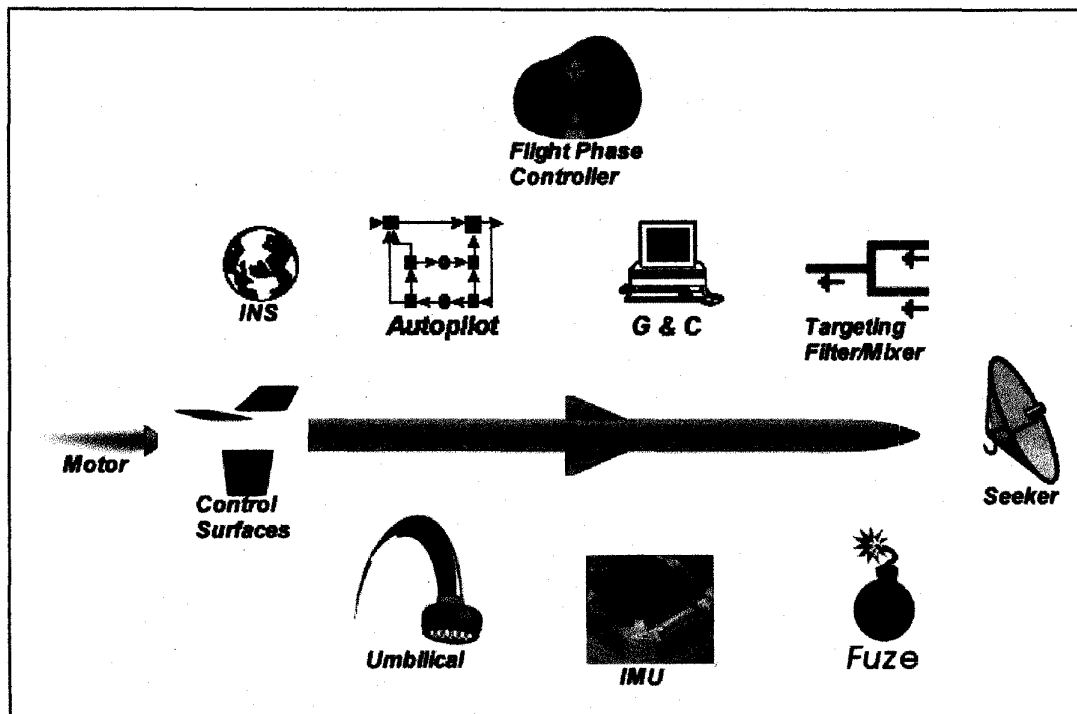

Figure 1. MSTARS Munition Model Components

AFRL/MNGG customers are often working on technologies for use in future weapon systems. Performance requirements for these systems are often vague and incomplete. Such requirements typically include high-level operational requirements such as launch range, and include high-level physical constraints such as weight and size. The vague nature of requirements at this level allows much leeway for design creativity in the simulation process.

Results from a recent in-house concept study[2] performed by AFRL/MNGG indicate that to accomplish successful risk reduction in the formative stages of concept development through simulation, it is necessary to address the simulation development and analysis process from a structured systems approach. There are four key principles inherent in the activities relating to this approach:

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[2] Miniaturized Munition Capability (MMC) Analysis of Alternatives (AoA) Concept Study, AAC/DRPW

1. *Understand the requirement.* The design, development, and integration of simulation models is tightly coupled with the operational requirements and constraints imposed by the warfighter. Therefore, it is necessary to understand all munition operational requirements before any simulation development is initiated.

2. *Use a structured simulation development methodology.* A well defined, well structured methodology is crucial to building an effective simulation model and to building an efficient, smoothly operating simulation development team. This is true regardless of whether the development environment is visual or code-based.

3. *Emphasize reusable simulation components.* Simulation development should rely heavily on model reuse and shared data to reduce cost, reduce errors due to building components from scratch, save time, and to prevent model incompatibilities.

4. *Select analyses appropriate to evaluating critical performance requirements.* Thousands of meaningless simulation runs are no better than zero simulation runs. Only certain high level, but critical, performance characteristics can be evaluated for a conceptual munition. The simulations conducted and the subsequent analyses must be tailored and focused on answering specific questions about the critical performance issues.

In order to put any concept analysis methodology in perspective, it is necessary to understand the "big picture". The problem domain, being addressed here, is the development of munition concepts. The concepts meet user requirements and can be provided to other organizations for further refinement, actual end item development, and production. The elements of the big picture are addressed in Section 2.

Simulation and analysis are critical elements of Munition Concept Exploration process, as described in Section 2. To address these critical elements, AFRL/MNGG has developed a structured approach, making use of in-house tools and a visual simulation system. The methodology is described in Section 3 and embodies the four key principles discussed earlier.

2. The Big Picture

Figure 2 is the authors' depiction of a generic group of activities, which occur from the point where the warfighter defines a requirement through the process of munition concept exploration. The boxes shown in the diagram do not represent any specific DoD, Air Force, or AFRL process. The depiction was created by the authors for convenience to describe generic processes that could represent a number of different situations where concept exploration occurs.

The Munition Concept Development Process is the sequence of activities, resulting in one or more candidate munition concepts. The concepts are provided to a SPO or other organization for final concept selection, development, and production. The overall process is depicted as being comprised of two broad sub-processes: (1) Requirements Definition and (2) Munition Concept Exploration. These two processes have been further divided into a series of sequential overlapping phases, adapted from the well-known Modified Waterfall Model, which allows a return to previous phases if needed. The following sections describe each phase.
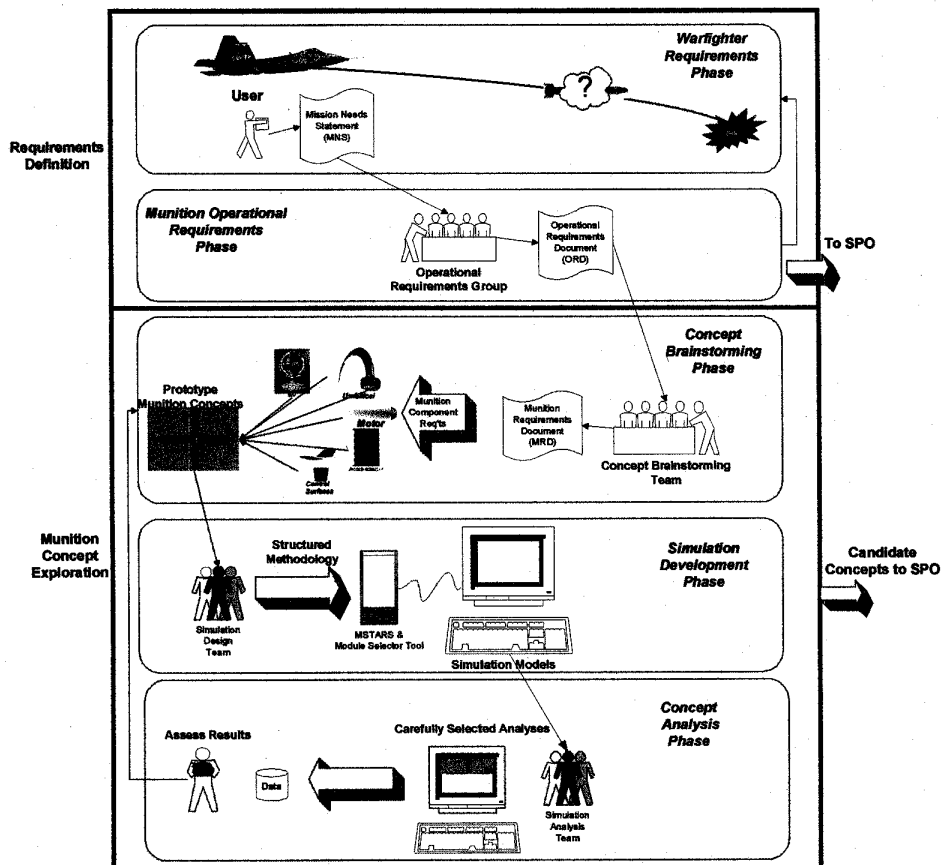

Figure 2. Munition Concept Development Process

2.1 Warfighter Requirements Phase

The Requirements Definition process begins with the Warfighter Requirements Phase, which defines the mission level requirements of the warfighter from launch to impact of the weapon system. This phase takes a problem-oriented approach in describing the mission need in broad terms, as shown in Figure 3. The operational command, the owner of the phase, is continuously evaluating the current weapon systems against the ever-changing threat environment. If the threat changes significantly so that the current systems are unable to counter it with a change in doctrine, tactics, training or organization, then the operational command generates a new requirement, which is specified in a Mission Needs Statement (MNS). A typical MNS may address such areas as:

- Multiple kills per pass
- Multiple ordnance carriage
- Adverse weather capability
- Medium-to-high altitude accuracy
- Capability against hard targets
- Carriage on multiple aircraft
  (e.g. F-15, F-16, F-18, F-117, B-2)
- Increased effectiveness
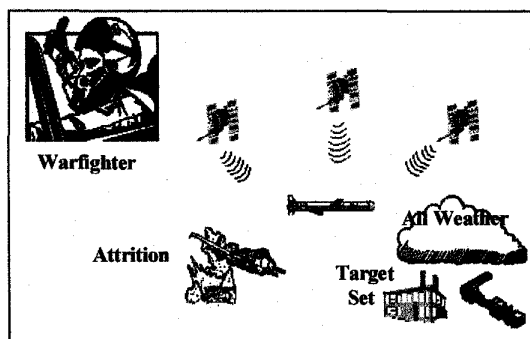- Reduced susceptibility to countermeasures

Figure 3. Warfighter Requirements

2.2 Munition Operational Requirements Phase

The warfighter requirements are further refined during the Munition Operational Requirements Phase, which refines the MNS from broad statements into more specific munition operational requirements. This phase is solution-oriented: it describes a detailed approach to solving the warfighter mission needs problem. The Operational Requirements Group, which could be one of several organizations, addresses mission needs from all aspects of operation across the entire life cycle of the system; and is

ultimately responsible for the development of the new munition system. The group must gain a sound understanding of the warfighter needs, to achieve a proper balance between cost, schedule, and performance considerations. The Operational Requirements Group produces the Operational Requirements Document (ORD), which specifies requirements for such things as:

- Aircraft integration issues
- Cost and scheduling
- Survivability
- Effectiveness
- Threats
- Performance
- Logistics
- Mission planning
- Load-outs
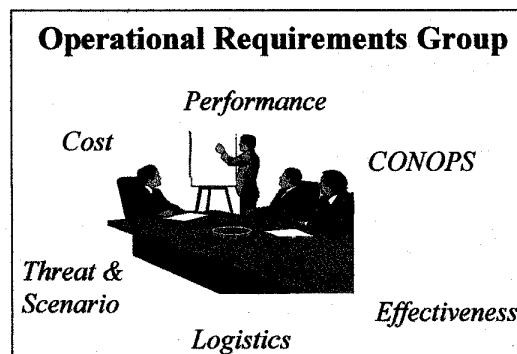
Figure 4. Operational Requirements

The Operational Requirements Group assembles other commands to investigate the issues laid out in the ORD. Sufficient data is collected from the commands so that a recommendation for a new weapon system can be made to the warfighter.

This phase marks the end of the Requirements Definition process. The resulting requirements are extremely important to the subsequent concept formulation and analysis, detailed in Sections 2.3 and 2.4.

2.3 Concept Brainstorming Phase

The Concept Brainstorming Phase marks the beginning of the Munition Concept Exploration process. This process, the main interest of this paper, takes the previously developed requirements and ultimately transforms them into effective candidate munition concepts, which could meet user needs.

The purpose of the Concept Brainstorming Phase is to match munition subsystem design choices against performance requirements, and to eventually identify one or more munition concept prototypes suitable for further study using simulation. The munition operational requirements will impose restrictions on the type of guidance law, autopilot, navigation system, airframe, and propulsion system, which could be selected for use. The Concept Brainstorming Team identifies all applicable technologies (Figure 5), selects those that best suit the requirements, and integrates them to form one or more "paper munitions" that meet the performance requirements. It is desirable that there be several "paper munition" concepts that meet the requirements. Each munition concept is defined in sufficient detail such that the Simulation Development Team, the next players in the process, will have a meaningful starting point for building a simulation of the concept.
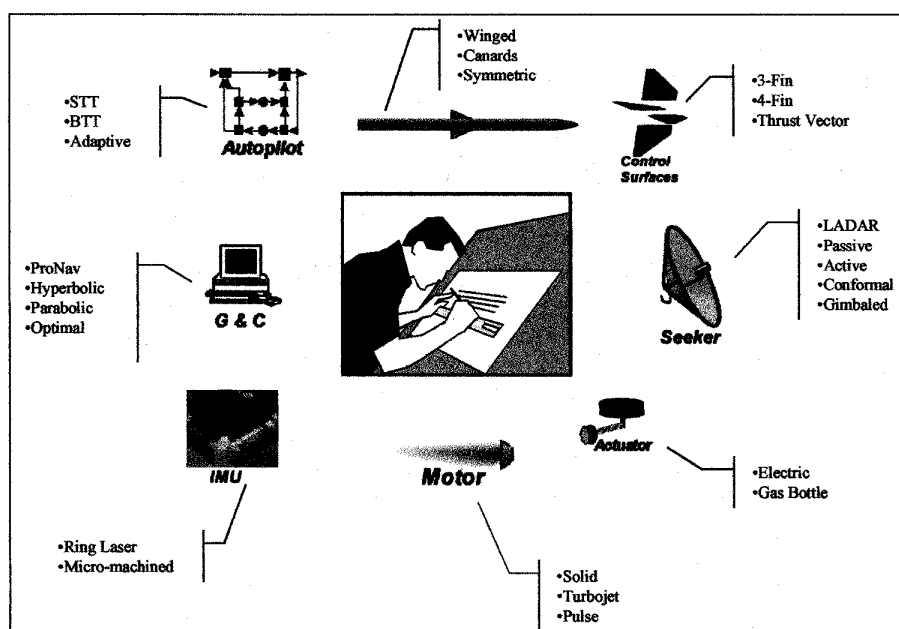

Figure 5. Munition Subsystem Technologies

Although simulation has not been mentioned as a part of this stage, often the paper study is refined with the aid of high level simulation tools, such as three-degree-of-freedom (DOF) simulations. These high level tools aid in verifying preliminary concept design prior to initiating the Simulation Development Phase.

2.4 Simulation Development Phase

In the Simulation Development Phase, the "paper munition" concepts, resulting from the previous phase, serve as the blueprint for the concept simulation models. An organized development approach is used and, in the case for AFRL/MNGG, existing components within the MSTARS library are pulled together to form a prototype. The component models are exchanged and/or modified to satisfy the munition operational requirements. Figure 6 gives an example of a typical simulation and its associated technology components.
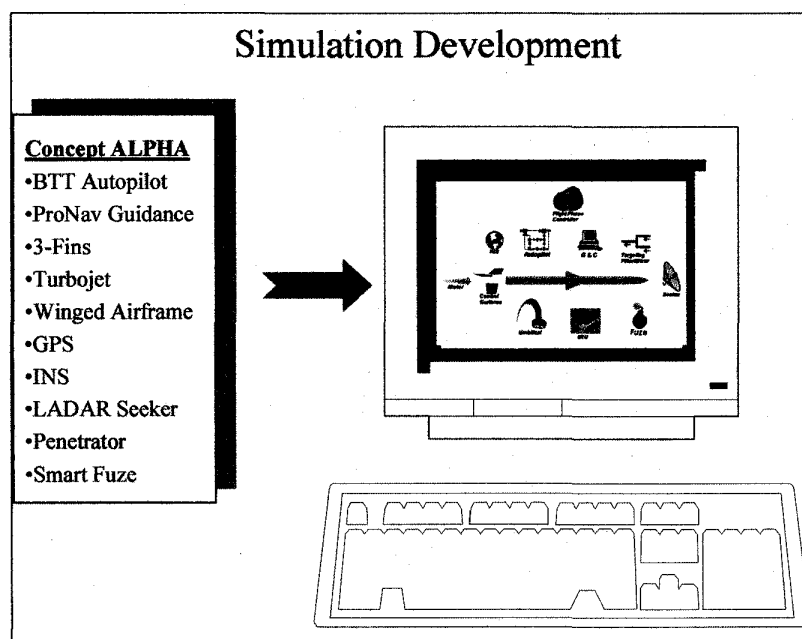
Figure 6. Simulation Development

To improve the effectiveness and efficiency of the simulation development procedure, MNGG has developed a structured methodology, which uses in-house software tools. For each concept, the simulation developed is much more detailed than a 3-DOF simulation, which might have been used in the previous phase. The methodology and the simulation development activities are described in detail in Section 3.1.

2.5 Concept Analysis Phase

The last phase, Concept Analysis, provides an in-depth study of the munition concept performance capabilities. The purpose is to demonstrate the general capabilities of the concept and to verify that critical warfighter requirements have been met. Additionally, comparative simulation results are used to rank the concepts defined by the Concept Brainstorming Team.

It is critical that appropriate analysis objectives be defined, which are keyed to questions about munition performance. Analysis planning, which is initiated in the Simulation Development Phase, is important to determine the requirements for simulation fidelity, identification of analysis data, and simulation functional requirements (such as multi-run capability). More details about this phase are found in Section 3.1.

After preliminary analysis, the Concept Brainstorming Team may find it necessary to correct the original concept specifications due to design errors that were not evident during the Concept Brainstorming Phase. Other concepts may drop out of consideration altogether due to extreme poor performance. The remaining concepts are further evaluated and the results are used to rank the concepts with respect to performance capability relative to the requirements. It should be noted that cost analysis, a critical activity, is conducted during this phase. However, the performance aspect of the analysis process is the focus of this paper.

3. Structured Design and Analysis Methodology

The structured methodology begins during the Concept Brainstorming Phase. The methodology encompasses the four principles discussed in Section 1. The Concept Brainstorming Team (Section 2.3) uses the specifications generated during the Munition Operational Requirements Phase to develop a single, or set of alternative munition concepts. Each requirement will result in some notional ideas from the team regarding subsystem technologies, which could be used to help the munition meet the requirement. Subsystem technology selections may be mutually exclusive or may result in degraded or enhanced performance when used together. Thus, there are many factors to consider. An organized approach is useful to ensure that all critical issues have been considered. Quality Functional Deployment (QFD) or other such approaches can be extremely helpful in determining a meaningful set of concepts.

The MNGG approach does not require any specific technique at this time for generation of the munition concepts. However, the result should be one or more concepts, which are capable (from a gross perspective) of meeting user requirements. Several steps, accomplished during the Concept Brainstorming Phase to arrive at the munition concepts, are repeated in greater detail during the Simulation Development Phase.

Most of the methodology and tools developed by AFRL/MNGG falls in the simulation development and analysis areas. Section 3.1 describes the Simulation Development Approach and Section 3.2 covers the Analysis Approach.

3.1 Simulation Development Approach

The activities described in this section are directly applicable to the Simulation Development Phase described in Section 2.4.

To construct the simulation of a concept, it is useful to look at the munition from both a functional point of view and from an object-oriented point of view.

A functional decomposition of the munition's operational modes separates the primary system functions into successively more detailed processes and defines the data flow between the processes. It provides good visibility into the various critical processes, which occur during weapon flyout. For example, a flight profile for a typical air-to-surface smart weapon can be partitioned into five modes of operation:

- Pre-launch
- Post-launch
- Mid-course
- Pre-terminal
- Terminal

The functions performed during each flight mode are examined to highlight overall simulation requirements and subsystem interaction, based on performance requirements of interest. Analysis of these flight modes can also suggest simulation architecture design decisions, which can make the simulation model more intuitive and effective.

Based on the desired performance analysis to be conducted, a description of data requirements, including inputs and outputs, should be formulated. A description of the data should include the volume and frequency of data to be processed, as well as any specific formats and limitations. These data requirements are critical to the success of the Concept Analysis Phase, discussed in Section 2.5.

An object-oriented view of the simulation, combined with the concept hierarchy, will provide insight into the subsystem model requirements. A Requirements Traceability Matrix (RTM) is produced during the Concept Brainstorming Phase, to ensure that selection of technologies and subsystems relate to the munition requirements. The RTM is further used during simulation development to identify requirements for the munition subsystem models and the simulation architecture.

Building the simulations is greatly aided by using a library of reliable, reusable subsystem model components. The library components, created over years of simulation development, have been through an extensive design, testing, and validation process. The result is a savings in overall design time by maximizing model reuse. The best starting point for a model prototype is a complete, existing, operational munition model, which has the same functional characteristics and many related subsystems as the intended final concept. A top-level description of this process is given in Figure 7.

One of the critical activities that must be accomplished is identification of the subsystems of the model prototype that requires modification in order to meet system requirements. Redesign may not necessarily involve the restructuring of an existing model, but may only require modification of model attribute data, such as aerodynamic or thrust data. In any event, a sequence order for redesign must be established to minimize the need for redesigning subsystem models repeatedly.
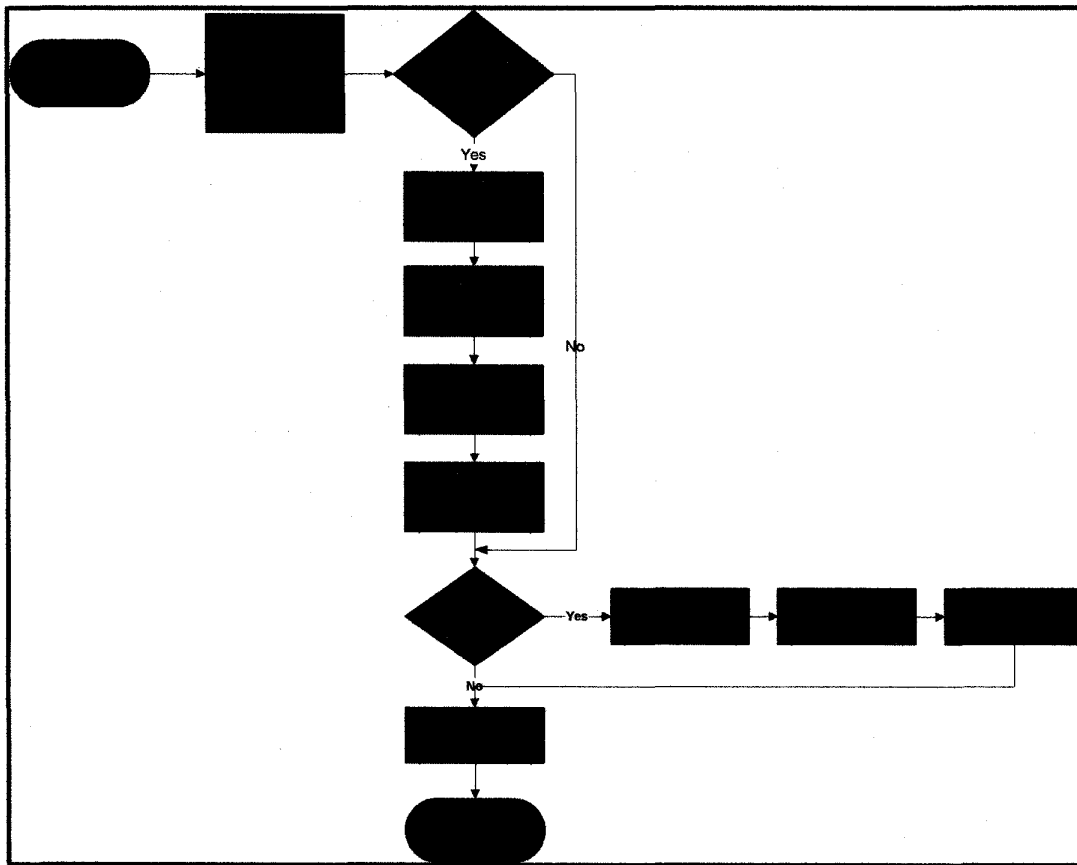
Figure 7. Simulation Development Process

A procedure to determine the subsystem modification sequence has been translated into an AFRL/MNGG in-house software utility called the Module Selector Tool (MST). The MST provides an automated means to establish the optimum sequence order that component modules should be modified. The MST allows the user to select a set of munition subsystem components, specify the components that will require modification, and determine the sequence in which the modifications should occur. It is important to note that the procedure works for a collection of existing models and will not address missing technologies or components. The user may find it necessary to include a "placeholder" for a missing component, ascertain its influences on other components, and then reconfigure the MST.

Figure 8 shows a screen shot of the Module Selector Tool, which consists of four panels: the Module Selector, the Edit Selection, the Dependency Matrix, and the Output panels.

The first user-input panel, the Module Selector (Figure 8), consists of an itemized list of munition subsystem components contained in the MSTARS library. The components are generic enough to allow the user to create a functional prototype munition. The Edit

Selection panel, also a user-input routine, enables the user to specify the components that may require modification in order to meet functional requirements. Associated with each component is a "dependency bin" that sums the effects of modifying dependent components. The logic for determining the dependencies results from a heuristic approach and requires knowledge of the functional dependencies of the models. If a component is selected for modification, then a value of 1 is added to the dependency bin of every component affected by the modification. The tally is used to "weight" the components and to determine the modification order. The higher the number associated with a component, the later in the redesign phase it falls, thus eliminating adverse affects on a previously redesigned component. The components and weights appear in the Output panel as well as on an additional view that provides a sort and a refit schedule.
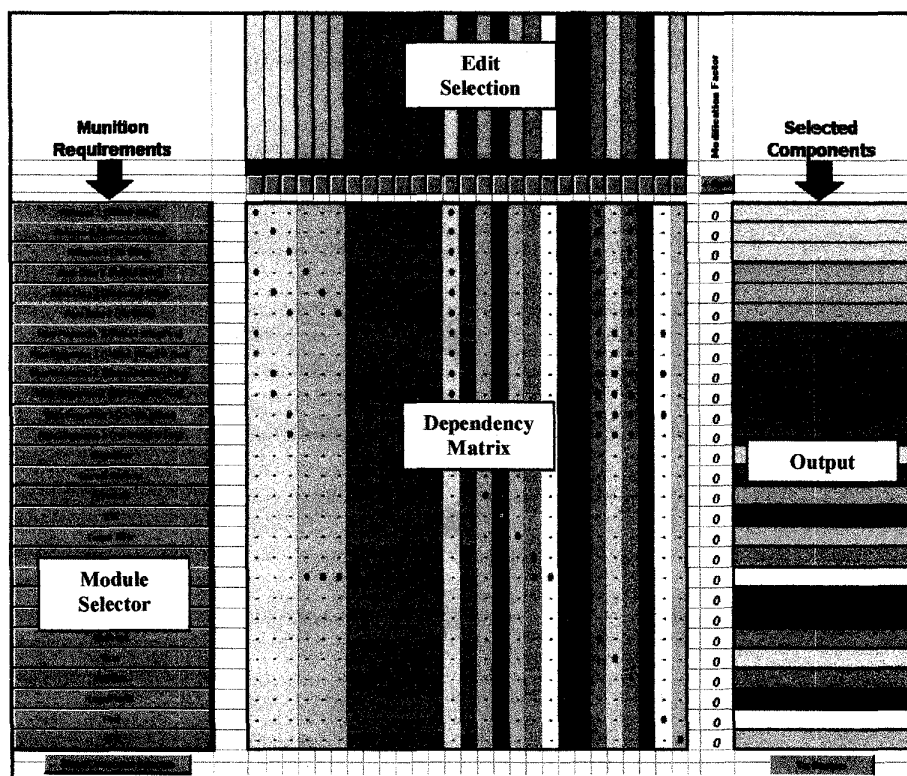

Figure 6. Module Selector Tool (MST) Screenshot

The Dependency Matrix panel is merely a graphical representation of the component dependencies and serves as a sanity check.

When the modification order has been determined, the module modification procedure begins. First, the library component is retrieved from the MSTARS library. The module is customized to reflect the requirements and specifications obtained in the Munition Operational Requirements Phase (this could also be a higher level requirement generated earlier in the overall process). After all changes have been made, an independent reviewer (e.g. another team member) is asked to review the work. The reviewer checks

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for errors in design, format, and completeness. This step is necessary because it gives an outside perspective to the work. If no discrepancies were found, the component is passed to another team member for thorough testing. Here, inputs, chosen so that each branch of the module is executed, are fed into the module. The actual outputs are collected and compared against expected outputs to verify that the component is operating correctly. If any discrepancies were found, the module is sent back to the modification step for corrections. The procedure continues until both the modification and testing steps are completed successfully for all components that were marked for change with the MST (refer to Figure 6).

The simulation build process is complete when all modules have been modified and tested, as necessary. The simulation is built by successively interfacing related components. For example, the first step of the build may begin with the guidance computer. The next logical component addition is the autopilot since the outputs of the guidance computer are the inputs to the autopilot. After each new component is added, tests are performed to ensure that the integrated components are working together correctly. This procedure continues until all components have been connected together to form the new munition model.

The last stage of this phase is simulation verification and acceptance testing. The acceptance tests are end-to-end systems level tests and must occur prior to analysis. These tests check the basic functionality of the munition system, such as:

- munition stability
- guidance and navigation accuracy
- propulsion functionality
- other similar functions

If the munition model fails the acceptance tests because of a component implementation error, the component is corrected, tested, and integrated by following the procedure outlined earlier. If the failure is a result of design error, the error is isolated and a re-evaluation by the Concept Brainstorming Team is required.

The end product of the Simulation Development Phase is a set of verified simulations, representing each of the munition prototypes developed by the Concept Brainstorming Team.

3.2 Analysis Approach

The activities described in this section are directly applicable to the Concept Analysis Phase described in Section 2.5. To accomplish the analysis, the simulation is exercised through a series of scenarios, which establish performance boundaries and capabilities.
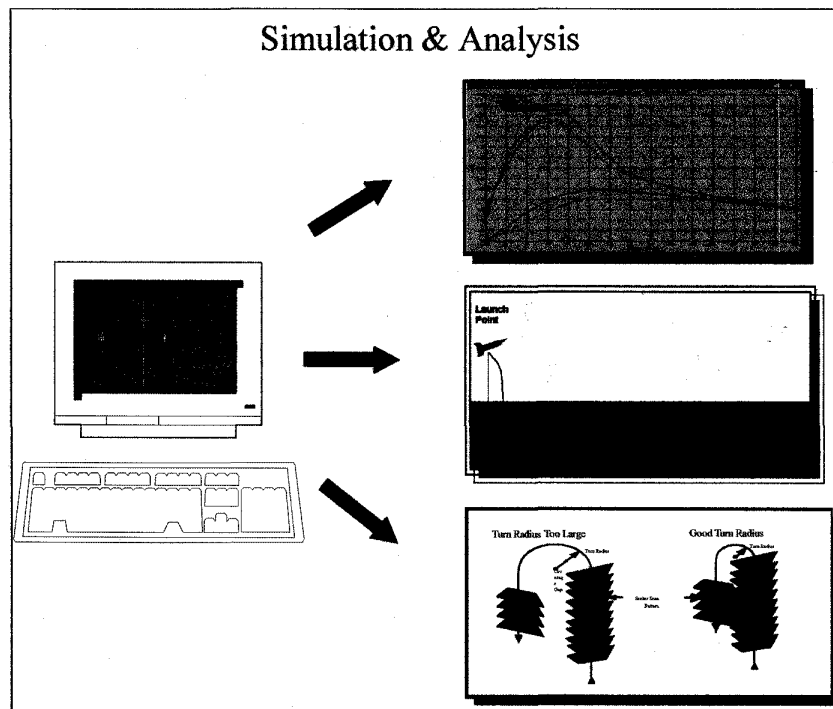
Figure 7. Simulation and Analysis

The areas for analysis must be carefully selected based on the performance criteria, outlined in the ORD. In fact, the performance criteria drive the fidelity and functional requirements of the simulation. For this reason, the identification of the analysis requirements is accomplished during the Simulation Development Phase. Areas for analysis may include:

- munition minimum/maximum range
- maneuver capability
- terminal performance (i.e. impact velocity, impact angle, and miss distance)
- operational environment
- any number of other areas

Based on the initial analysis data, additional analysis may be required to perform trade-off studies, which address particular system components and their impact on overall

performance. The trade-off studies provide information for risk reduction, technology investment decisions, and serve to refine the concept.

All performance data generated from the simulation and analysis effort is collected and compiled by the Operational Requirements Group. The data is used to reject unacceptable concepts. The final refined concepts and performance analysis results are typically provided to a SPO, or similar organization, for use in selecting one or more concepts for possible development and production.

4. Conclusion

For convenience and clarity, MNGG has depicted the overall concept development process as consisting of two sub-processes: (1) Requirements Definition and (2) Munition Concept Exploration. Activities occurring in the two processes have been mapped into five phases. Concept Exploration has three phases, and it is in the latter two phases, involving simulation and analysis, where MNGG has developed an organized methodology and in-house tools to make the activities more efficient and effective.

The various activities of the simulation and analysis methodology employed by MNGG embody four key principles:

- ***Understand the requirement.***
- ***Use a structured simulation development methodology.***
- ***Emphasize reusable simulation components.***
- ***Select analyses appropriate to evaluating critical performance requirements.***

In the course of developing the methodology, MNGG has developed in-house software tools, which aid in making the simulation development and analysis more effective. These include:

- ***The MSTARS Simulation System***
- ***The Module Selector Tool (MST)***

The methodology and tools were developed during a recent major effort to analyze a set of munition concepts. Since that effort, the methodology and tools have been further refined and are continuing to evolve. Practicing such a methodology and using effective tools can tremendously reduce the time required to conduct munition concept analysis and can make that analysis much more effective.