Foundation of Structured Architecture, System & Cost Modeling

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Abstract: Modern software packages exist to estimate system cost early in the system development and procurement process. This paper begins the development of a structured systems engineering approach to system design. This paper defines a standardized modular diagram for a RADAR system applied to military applications in the aerospace industry. This modular diagram with sub-system block elements will be used to create a system model. The standardized modular diagram will also be used to create a cost model, using the same modular sub-system block elements and industry standard historical cost data. The commercially available software packages which estimate system cost are limited in their ability to aid in system optimization towards multi-objective cost and performance goals, as many require a completed system design. Methods are needed to determine which components in a system would benefit from additional modeling such as using a multiphysics approach, and which design approach provides the best value (cost vs. performance) to the system. These methods are needed during concept development to aid in system scoping and cost estimation. To illustrate the benefits of cost optimization during early stages of design, this paper describes a sensitivity analysis approach applied to the design of an engineering system. This process seeks to use sensitivity analysis and a spiral design process to determine which cost drivers have the highest influence on overall system cost, and to realize high system performance while minimizing costs.

This work demonstrates that a system can be defined as a standard set of block diagrams for an airborne RADAR for military applications created by integrating a wide sample of the available examples. And where each of the example block diagrams could be considered a subset of the more generalized form. This work describes using the generalized block diagrams to create a WBS structure as the foundation for both a system model and a cost model. This work applies a sensitivity analysis to a cost model in order to direct a system designer towards a trade study for the purposes of system optimization. And finally, this work introduces a method using component cost sensitivity to determine the range of possible cost improvements to bound project return on investment.

I. Introduction

There are several very good commercially available cost estimation packages. To use these packages, first a system must be defined. The system must be defined in terms of hardware blocks. The hardware blocks can be arranged with a hierarchy such as a Work Breakdown Structure (WBS). Once the system is defined, the system can be entered into the cost estimation package. The package essentially converts each hardware component into a corresponding cost. In this way the cost of a system can be estimated.

In order to analyze a system, it is necessary to have a system upon which to perform the analysis. Typically, for a new effort a system is defined from the perspective of the designer where certain features were a priority to the respective designer. Those priorities are reflected in the various block diagrams which are produced and can be seen as areas of increased fidelity while other areas of the block diagram are simplified or even combined with other functions into one sub-block. For the current example of an airborne RADAR for military applications there are many example block diagrams within the existing literature. However, although the end application is the same, the various block diagram examples vary widely. It can be considered that the block diagrams were tailored for each application and demonstrate the priority of the respective designer. This paper demonstrates the development of a generalized set of block diagrams for an airborne RADAR for military applications. The block diagrams were created by integrating a wide sample of the available examples where each of the examples could be considered a subset of the more generalized form.

The focus of this paper will be divided into four main topics: block diagram development, systems engineering model development, systems cost model development, and sensitivity analysis concepts applied to a system cost model.

The first section, Block Diagrams, will discuss the available literature on the topic. Specifically, research into the existence of industry standard block diagrams for an airborne based RADAR for military applications and subsequently the development of one where a standard did not exist. The level one system RADAR block diagram is defined along with the level two sub-blocks: antenna, transmitter, synchronizer, receiver, etc. A solid block diagram is frequently the best way to begin a new design. It becomes a pivot point upon which everything else is developed. All major radio frequency (RF) interfaces and divisions of functions can be seen (digital control will not be addressed).

In the second section, Model The System, a structured approach to system engineering is started and the elements of the block diagram are described. The elements are ready to be loaded into a system engineering tool and form the basis of future work which would be expanded to include operational view diagrams, logical view diagrams and other system engineering artifacts.

In the third section, Model The Cost, a structured approach to system cost modelling is discussed and the format of the model is described. The cost model utilizes the same functional blocks as defined in the block diagram section. This forms the basis for future work which will eventually lead to a robust modular cost model to describe a range of RADARs and their associated estimated costs.

In the fourth section, Sensitivity Analysis Applied To A Cost Model, a concept is introduced whereby a sensitivity analysis could be applied to a cost model to direct a system designer towards a trade study for the purposes of system optimization. In addition, it is shown that a sensitivity analysis provides an upper bound of potential cost improvements which then forms the basis for a Return On Investment (ROI).

This work is novel in that it demonstrates that a system can be defined as a standard set of block diagrams for an airborne RADAR for military applications created by integrating a wide sample of the available examples. And where each of the example block diagrams could be considered a subset of the more generalized form. This work is novel in that it describes using the generalized block diagrams to create a WBS structure as the foundation for both a system model and a cost model. This work is novel in that it introduces a sensitivity analysis applied to a cost model in order to direct a system designer towards a trade study for the purposes of system optimization. And finally, this work is novel in that it introduces a method using component cost sensitivity to determine the range of possible cost improvements to bound project return on investment.

II. Related Work

A. Literature Assumptions and Search Terms.

The available literature was consulted, primarily through the use of Google searching. The assumption of the author was that a standardized block diagram for an airborne RADAR for military applications already exists. The assumption was that there was a standard upon which all designs were based. Research was done using keyword search terms such as "standard block diagram", "RADAR block diagram", "airborne RADAR block diagram", etc.

B. Literature Results.

For each effort, many search results were obtained. There were countless block diagrams for all types of RADARs. And, for the specific platform of airborne RADAR, again, there were many different results. However, although the results varied each version of a block diagram had some similarities. The differences appeared to be due to the focus of the respective system designers. In other words, if the designer's focus was upon a specific sub-function, that area of the block diagram had significantly more fidelity. Conversely, other areas of the block diagram would be abbreviated or even combined with other sub-functions. In this way the designer could highlight an area or sub-block for increased emphasis.

III. Block Diagrams

A robust block diagram is frequently the best way to begin a new design. And it is a recommended first step. It is not uncommon for engineers to jump right into a design and begin designing. Each engineer responsible for a portion of the system has ideas on how to best proceed. And frequently those best ideas are competing rather than complimenting one another. Therefore, a robust discussion early on regarding system goals is critical. Without a clear set of system goals, it is unlikely a system will be designed correctly on the first attempt. And a first step towards defining those goals is to create a block diagram. It becomes a pivot point upon which everything else is developed. All major interfaces and divisions of functions can be seen.

Not only do block diagrams align system and sub-system designers but also block diagrams are key tools for cost analysts. The most obvious area of contribution is defining interfaces. With a good visual representation, interfaces are considered, and meaningful requirements can be created. Those requirements affect many variables including cost, performance, life span, operation, etc. A cost analyst does not need to be a system designer. But having some familiarity with the basic building blocks of the system is critical. A good cost analyst should actively participate in the early generation of system block diagrams to help influence the direction of the system design.

A. Interfaces and Functions.

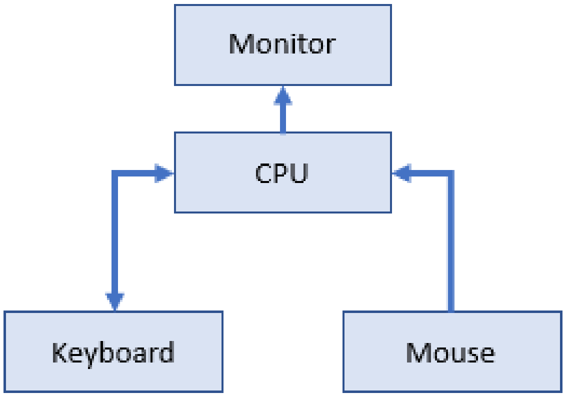


Figure 1. Computer Block Diagram.

Figure 1 shows a simple block diagram of a standard computer. In this case, the computer is made up of four sub-blocks. For purposes of this paper, the entire computer will be considered Level 1 while the sub-blocks indicated in the figure will be considered Level 2.

From this figure, the central processing unit (CPU) is the main sub-block in that it interfaces with all the other blocks. And none of the other sub-blocks talk directly to one another. By observing the arrows, some of the interconnects are 2-way communication, such as between the keyboard and CPU, while other interconnects are 1-way communication, such as from the CPU to the monitor. In addition, there clearly are four blocks. Each block is labeled by function. Each block has distinct responsibilities for the system performance. And it could be clearly defined what those interfaces should be for those blocks to communicate with one another. For a team designing a computer system, this very simple block diagram already contains very valuable information which will help guide the designers towards a successful system design. This is the value of a block diagram. It can be done early, simply, and it can contain an enormous amount of critical system information.

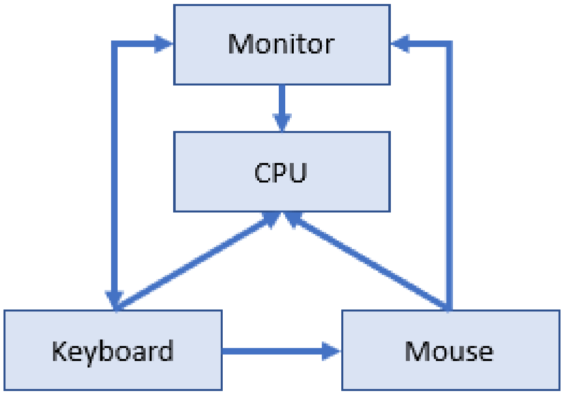


Figure 2. Computer Block Diagram.

As a comparison, imagine a block diagram as the one indicated in Figure 2. Although the blocks are the same as Figure 1, the interfaces are clearly more complex. And the interactions between the blocks more closely resemble a network rather than a command-and-control structure such as that indicated in Figure 1. Clearly, block diagrams offer a shorthand to an enormous amount of information in a simple easy to read format.

B. Standardized RADAR Block Diagram.

With no clear standardized block diagram, the author used the available information to piece together one comprehensive solution. The goal here was to generalize the sub-blocks in such a way as to incorporate a wide sample of the available examples. Any sample block diagram could be considered a simplified, or tailored version of the more generalized form.

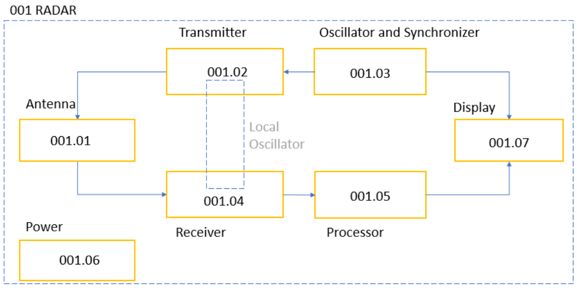


Figure 3. Generalized RADAR System Block Diagram.

Figure 3 is a generalized RADAR system block diagram for an airborne based military application. The outer dashed line can be considered Level 1, the complete RADAR System. The sub-blocks indicated in the figure comprise the Level 2 blocks and consist of antenna, transmitter, etc. This block diagram as well as the Level 3 block diagrams appear in the appendices.

What can be concluded here is that every airborne RADAR system for a military application will have an antenna. Antenna designs can vary widely. It could have any number of radiator elements: 1, 10, 100, 1000, etc. It could have any type of radiator: notch, patch, whip, etc. However, it most certainly will have some form of antenna. And so that sub-block appears in the block diagram. In this case it has been labeled 001.01 signifying the first (01) of the Level 2 sub-blocks. All of the sub-blocks have been correspondingly numbered. This will come up again within this paper when the WBS structure and models are discussed.

The block diagram also contains arrows which demonstrate the direction and flow of information between the sub-blocks. It can be seen that the directional flow is exclusively 1-way. It should be noted that this is limited to the signal flow including radio frequency (RF) interfaces. There could potentially be cases of multi-directional flow for purposes of digital control which are not addressed. For example, the processor might turn off the transmitter and then receive some feedback that the transmitter has indeed been disabled. However, that is a control signal and is not captured by this signal flow diagram.

The local oscillator appears as a dashed line and crosses into the transmitter and receiver as well as the white space in between. This is done because while those two sub-blocks require a local oscillator (LO) for operation, in some hardware configurations they have a resident dedicated LO, while in some configurations there is a separate sub-block dedicated to the LO function. And this representation is deliberately created to accommodate either physical hardware solution or implementation.

The descriptions for each sub-block (Level 1, 2, or 3) were generated in the same manner as the block diagrams. The available literature was widely explored, and the various descriptions were collected. Then, the various descriptions were combined into a higher order, more general version for which all descriptions could be considered a simplified, or tailored version of the more general versions presented here.

C. *Sub-Block: 001.01 Antenna.*

A numbering convention was selected, and each element is assigned a unique identifier. The numbering convention identifies hardware "Levels" (1, 2, 3, etc.). The antenna appears in Figure 4 as element 001.01 which was previously noted to designate the first of the Level 2 elements. The numbering convention was consistently applied throughout the development for the block diagrams, system model, and cost model.

The antenna is the coupling element between free space and the other RADAR elements. The antenna transfers the RADAR energy from the transmitter into free space. And the antenna collects the echo energy from free space and delivers it to the receiver for down conversion and processing.

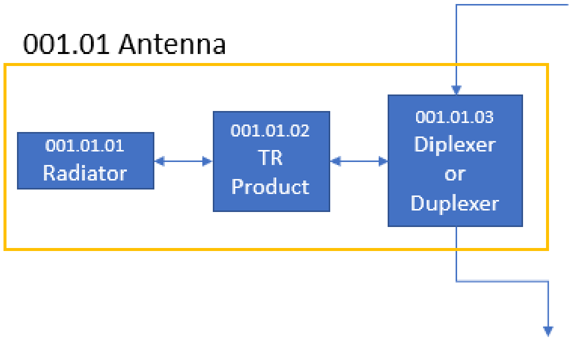


Figure 4. Antenna Block Diagram.

As illustrated in Figure 4, the antenna sub-block can be further decomposed into Level 3 blocks: radiator, transmit-receive (T/R) product, and duplexer. The element numbers have been assigned as indicated in the figure.

An anticipated criticism regarding this block diagram would come from the perspective of the hardware configurations. Typically, for an airborne system, there are two main hardware configurations. The first typical configuration is where each element is independent. Each element has a radiator and a T/R product. And then a bank of those channels is combined to make an array, a vertical configuration. The second configuration is where all the radiators are assembled in a bank of radiators, almost like a plate of radiators. And then those radiators are mated against a bank or plate of T/R products, a lateral configuration. A designer might argue that the image captured in Figure 4 is only one of the two possible configurations. However, the representation in Figure 4 is a functional view irrespective of the hardware configuration. Therefore, both configurations are applicable. The block diagrams contained within this document are created to showcase the functional sub-blocks and the associations between them. The diagrams were intended to satisfy all physical instantiations.

The radiator is an exchanger between the propagating waves and the electric currents. The T/R product is a device where common circuitry for both transmit and receive functions are combined into a single module or element. The duplexer in a high-power RADAR system is the element that switches the antenna path between the transmitter and the receiver paths for a system where the two paths share an antenna. It is also used to protect the receiver from high power transmissions entering directly from the transmitter.

D. Sub-Block: 001.02 Transmitter.

The transmitter appears in Figure 5 as element 001.02. The transmitter modulates, or up converts, the wave to a transmission frequency. Then, if required to increase the signal power before transmission, the transmitter amplifies the wave for the antenna to send into operating space.

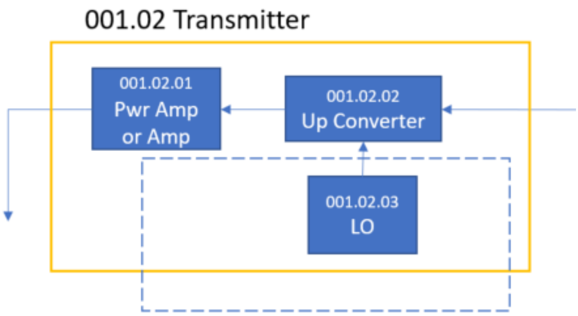


Figure 5. Transmitter Block Diagram.

As illustrated in Figure 5, the transmitter sub-block can be further decomposed into Level 3 blocks: power amplifier, up converter, and local oscillator (LO). The element numbers have been assigned as indicated in the figure.

The power amplifier is a device that converts a low power signal into a higher power signal. In the past, the high-power amplifier was more likely to be some sort of traveling wave tube. But certainly, the more contemporary approach would be a solid-state high-power amplifier. Regardless of the hardware configuration, the block diagram is a functional view and represents either approach. The LO is an oscillator which is used to change the frequency of the signal.

Local oscillators often employ some means of a phased locked loop (PLL). Typically, it is easier to have a stable oscillation when the frequency generated is low. And it is easier to generate a high frequency oscillation when the oscillation is less stable. By means of a PLL, it is possible to take the best of both and create a device which is stable at high frequencies. In the paper Digital Control Of Frequency Locked Oscillator, Microwave Journal March 2020, stable high frequency oscillations were achieved by locking a single oscillator to itself. It was accomplished by passing the signal through a long semi-rigid cable and then frequency locking to the time delayed reference.

The up converter is a nonlinear electrical circuit that creates new frequencies from two signals applied to it. Most commonly, this is accomplished with a mixer. In the case of a transmitter, the mixing product is a multiple of the sum of the input signal and the LO signal. The purpose of the up converter is to modulate the signal from the synchronizer for the antenna. But it is widely known that by means of a mixer, multiple harmonics are generated. And, by use of filtering, any higher order harmonic can be isolated, amplified, and used as the mixing product.

E. Sub-Block: 001.03 Synchronizer.

The synchronizer appears in Figure 6 as element 001.03. The synchronizer coordinates the timing of the RADAR. It generates timing pulses that are used to control the RADAR pulse repetition frequency (PRF). Signals are sent simultaneously to both the transmitter and the display to align the sweep echo pulses.

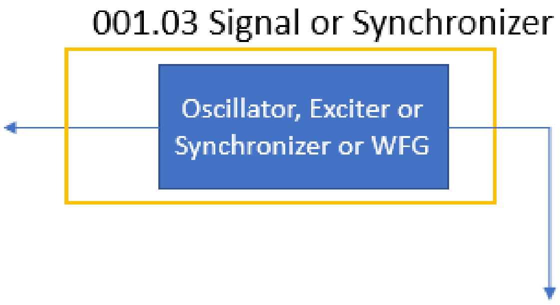


Figure 6. Transmitter Block Diagram.

The Synchronizer sub-block can be further decomposed into Level 3 blocks. However, for purposes of this analysis, the synchronizer will be considered as elemental, and cannot be further subdivided. This is done because there does exist a variety of synchronizer architectures and further analysis will need to be performed to determine a standardized Level 3 architecture. Thus, no element numbers have been assigned as indicated in Figure 6.

F. Sub-Block: 001.04 Receiver.

The receiver appears in Figure 7 as element 001.04. The receiver detects an incoming echo signal bounced off of a target, receives, amplifies, demodulates, and converts the analog signal to digital format for further analysis in the digital processor.

As illustrated in Figure 7, the receiver sub-block can be further decomposed into Level 3 blocks: low noise amplifier, down converter, intermediate frequency (IF) amplifier, filters, 2nd down converter, detector, and analog to digital converter. The element numbers have been assigned as indicated in the figure.

The local oscillator here is the same as that discussed in the RADAR and transmitter sections. As mentioned earlier, the LO is an oscillator which is used to change the frequency of the signal. In this application the LO is used to down convert a signal while in the transmitter it is used to up convert a signal. The low noise amplifier (LNA) boosts the signal while adding as little additional noise as possible. The goal is to maximize the signal to noise ratio (SNR) of the echo signal.

In a receive chain, the signal to noise ratio is determined primarily by the first element. The first element of the chain dominates the entire chain's performance. Low noise amplifiers, as the name suggests, are a special sub-class of amplifiers designed for this purpose. Therefore, an architect should assume an LNA as a first element.

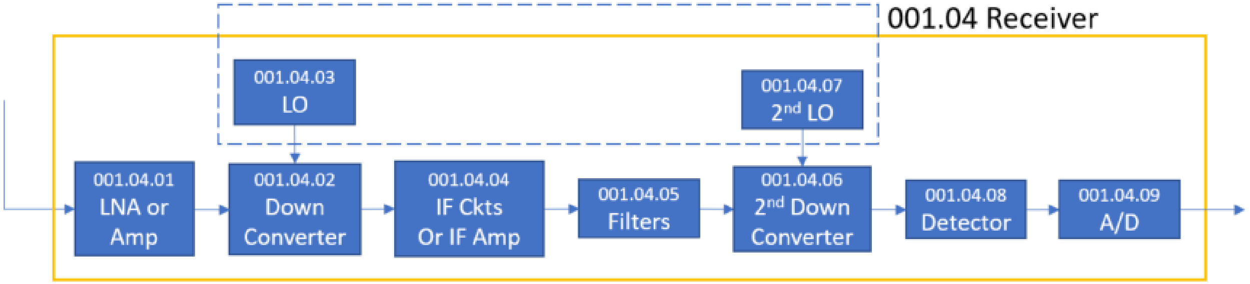


Figure 7. Receiver Block Diagram.

The down converter is a nonlinear electrical circuit that creates new frequencies from two signals applied to it. Most commonly, this is accomplished with a mixer. In the case of a receiver, the mixing product is a multiple of the difference of the inputs signal and LO signal. The purpose of the down converter is to demodulate the signal and the RF frequency of the LNA to a lower or intermediate frequency (IF) where amplification and filtering can be done more easily. Generally, multiple mixers would be used.

Later in the signal chain, the signal will be converted from analog to digital. The signal must be digitized for meaningful data processing of a modern system. At some future time, it may be possible to directly convert an X-band signal to digital, but in today's practical terms that is not yet possible. Therefore, the conversion is required. The detector and analog to digital (A/D) converter, as their names imply convert an analog signal into a digital signal. To convert the signal from analog to digital, a digital clock must be used. If the transmitted signal is "high," using the Nyquist criteria, the sampling frequency must be "higher." This is the fundamental limitation of the A/D converter. As mentioned, as time passes the technology is improving, but in today's practical solutions, the architect's options are still somewhat limited.

G. Sub-Block: 001.05 Processor.

The processor appears in Figure 8 as element 001.05. The processor decides if an echo is a target and determines if and how to present a depiction to the display. Typically, this may include number, location, and movement of targets.

The processor sub-block can be further decomposed into Level 3 blocks. However, for purposes of this analysis, the processor will be considered as elemental, and cannot be further subdivided. This is done because the processor is primarily a digital device, and the focus of this analysis is upon the analog path for the signals. Thus, no element numbers have been assigned as indicated in Figure 8.

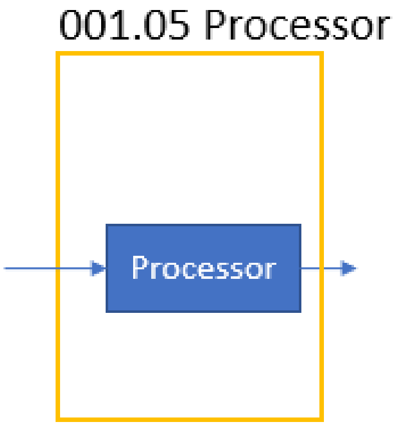


Figure 8. Processor Block Diagram.

H. Sub-Block: 001.06 Power.

The power block appears in Figure 9 as element 001.06. The power block converts the primary power from the platform to the required forms needed for each sub-block.

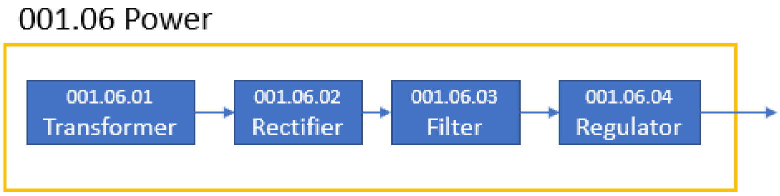


Figure 9. Power Block Diagram.

As illustrated in Figure 9, the power sub-block can be further decomposed into Level 3 blocks: transformer, rectifier, filter, and regulator. The element numbers have been assigned as indicated in the figure.

The transformer is a device which transfers electrical energy through electromagnetic induction. The transformer is comprised of coils. As current passes through a coil it generates an electro-magnetic field. If a second coil is placed within that field, a current is generated in the second coil. By adjusting the ratio of turns for each coil, a voltage can be stepped up or down. In a familiar power supply, such as for a laptop, the power supply converts 120 volts AC from the wall outlet down to 12 volts DC for use by the computer. The transformation from 120 volts to 12 volts, called a step down, is done by means of a transformer. Because the transformer is comprised of coils, the transformer is always the heaviest component in the power supply.

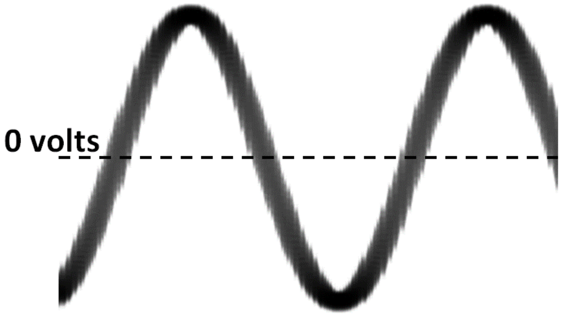


Figure 10. Sinusoidal Signal.

The rectifier is a device which converts electricity from AC to DC. The most common rectifier is a bridge rectifier and can be created with four diodes. For a sinusoidal signal (Figure 10) half of the time the voltage is positive, and half of the time the voltage is negative. Through the rectifier, the negative half cycle of the sinusoidal signal is flipped up to be positive (Figure 11). As a result, the wave form is now a series of positive going sinusoidal voltage "bumps," like humps of a camel's back.

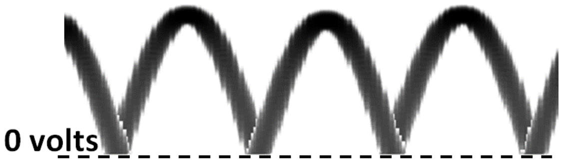


Figure 11. All Positive Voltages.

The filter is a device used to remove unwanted frequency components. After the voltage has been transformed into a series of positive going sinusoidal voltage "bumps," it is necessary to smooth it out. When the voltage value approaches zero the slope of the curve is negative. Once the voltage has reached zero volts, the voltage begins to rise and has a positive slope. The transition between a negative voltage slope and a positive voltage slope is instantaneous. The instantaneous nature of the voltage in the time domain corresponds to a high frequency effect in the frequency domain. By removing that high frequency component of the signal, by means of a filter, the corresponding waveform will be smoother.

The regulator is a device which stabilizes a DC voltage independent of the load current. The signal, post filtering, approximates a fixed DC value. However, the value is not stable. The voltage continues to have some residual effects from its sinusoidal origin. For use in a system, voltages must be stabilized. A regulator removes frequency components of a "dirty" DC signal and clamps it to a predetermined value. Post regulation, the signal is a "clean" DC value.

I. Sub-Block: 001.07 Display.

The display appears in Figure 12 as element 001.07. The display presents a depiction, in a usable form, of received targets. Typically, this may include number, location, and movement of targets.

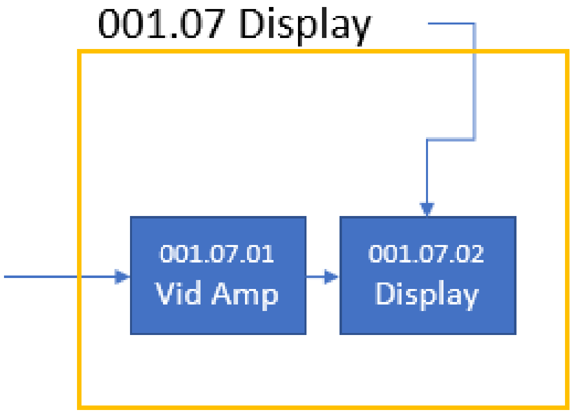


Figure 12. Display Block Diagram.

As illustrated in Figure 12, the display sub-block can be further decomposed into Level 3 blocks: video amplifier and display. The element numbers have been assigned as indicated in the figure.

The video amplifier is a device which is designed to process video signals. The display is a device which is used for presenting images and video. Typically, this would be a cathode ray tube (CRT) or more recently some type of liquid crystal display (LCD) such as a laptop screen or monitor.

IV. Model the System

Once a rigorous block diagram for a system has been created the next step is to begin modeling the system, or otherwise referred to as architecting a system.

Not only do system models align system and sub-system designers but also system models are key tools for cost analysts. System models include many artifacts such as documented requirements, documented use cases, logical view diagrams, operational view diagrams, etc. Just as with block diagrams, a cost analyst need not be an expert in all these areas but certainly a firm understanding would be most helpful. An awareness of system modeling and the related artifacts enables a cost analyst to better understand the system and then to estimate a cost with a higher fidelity. Just as with block diagrams, a good cost analyst should actively participate in the development of a system model to help define the system design.

There is a very important book on the topic entitled "Architecting Information-Intensive Aerospace Systems" by Dr. John M. Borky. In it, the author writes that architecting is done "to create systems and enterprises that are well organized, expandable and evolvable, robust under the stresses of real-world use, and affordable to own and operate. In short, the essence of the art and science of architecture is manifested in results that are beautiful in the eyes of their users while satisfying those users' practical needs."

Robust models created through Model-Based Systems Engineering (MBSE) are the foundation of the entire System Engineering (SE) process and provides a clear and unambiguous definition of the system.

While there are several tools which may do similar functions, for architecting the system in this paper, the COTS software tool used was chosen because it contained all the tools required to document requirements, document use cases, create logical view diagrams, operational view diagrams, and other system engineering artifacts.

A. System Modelling Approach.

When creating a structured architecture utilizing a COTS system engineering tool, one very useful structure is indicated in Table 1.

System Engineering Model
Components
Internal Block Diagrams
Packages
a_Requirements
b_UseCases
c_Structure
d_Behaviour
e_Data
f_Services
g_Context
PredefinedTypes (REF)
z_Default

Table 1 System Model Structure.

These items are referred to as packages. This is a very solid structure and provides an architect with designated locations for creating system artifacts. With a structure such as this, virtually any artifact required, or created, can be sorted, and stored into one of these packages.

B. RADAR System Modelling Structure.

An indentured set of numbers was created for this system and appears in Table 2. In Table 2, the hierarchy of the system design with Level 1, 2, & 3 sub-block names and numbers can be seen. These numbers form the basis for a Work Breakdown Structure (WBS).

Level 1	Level 2	Level 3	Block Name
001			Radar
	001.01		Antenna
		001.01.01	Radiator
		001.01.02	TR Product
		001.01.03	Duplexer
	001.02		Transmitter
		001.02.01	Power Amplifier
		001.02.02	Up Converter
		001.02.03	Local Oscillator
	001.03		Synchronizer
		001.03.01	Synchronizer
	001.04		Receiver
		001.04.01	Low Noise Amplifier
		001.04.02	Down Converter
		001.04.03	Local Oscillator
		001.04.04	IF Amplifier
		001.04.05	Filters
		001.04.06	2nd Down Converter
		001.04.07	2nd Local Oscillator
		001.04.08	Detector
		001.04.09 Figure 10	Analog to Digital Converter
	001.05		Processor
		001.05.01	Processor
	001.06		Power
		001.06.01	Transformer
		001.06.02	Rectifier
		001.06.03	Filter
		001.06.04	Regulator
	001.07		Display
		001.07.01	Video Amplifier
		001.07.02	Display

Table 2 Indentured System Numbering Structure.

C. Work Breakdown Structure (WBS).

A Work Breakdown Structure (WBS) (MIL-STD-881D) is a tool used to define a project in discrete work elements in a hierarchical format. It displays and defines the product, or products, to be developed and/or produced. It relates the elements of work to be accomplished to each other and to the end product. As described in the *smallbusiness* website, "The main purpose of a WBS is to reduce complicated activities to a collection of tasks." It is a very useful management tool. By arranging the architecture in such a manner, not only will it describe the breakdown of the hardware from Level 1 to Level 2 and so on, but it can also form the foundation of the set of tasks required to design the hardware. For example, a radiator is designated as block 001.01.01. The design cycle for any block, such as a radiator, will likely follow a standard design cycle: requirements, preliminary design, detailed design, and integration, verification & validation (IV&V). Those are phases which are made up of tasks and could be designated with the further indentured designators:

001.01.01.01 Requirements Phase
001.01.01.02 Preliminary Design Phase
001.01.01.03 Detailed Design Phase
001.01.01.04 IV&V Phase

These phases could additionally be designated with even lower-level numbers and even more specific tasks. The point is, creating a system structure with an eye towards a WBS is a best practice and frequently is a contract requirement.

D. RADAR COTS System Model.

The RADAR system demonstrated earlier as a set of block diagrams can be loaded into a COTS system engineering modeling tool (Table 1). The information from the block

Figure 12

diagrams could be loaded into the requirements package. The various block diagrams can be loaded into the structure package. And, in general, all system artifacts could be documented within the COTS tool.

The numbering and indenture of the entries should remain consistent with that presented in the earlier sections of this paper (Table 2). The specifications within the requirements package should also be consistent with the information contained within the block diagrams.

A robust system model helps to align system and sub-system designers and are key tools for cost analysts. A good cost analyst need not be an expert in system engineering tools. But some familiarity with system engineering tools would be very advisable. And early participation in a product life cycle will help a cost analyst to not only influence the direction and the development of the system design but also to then be in a far better position to generate system cost estimates.

V. Model the Cost

Once a rigorous block diagram and system model for a system has been created the next step is to begin modeling the system cost. As mentioned, with early participation in a product life cycle a cost analyst will be in a far better position to generate system cost estimates.

A new emphasis introduced here is a structured approach which includes a modular approach to modeling the system cost. At a later phase in the system design, it will be necessary to perform trade studies. The most common trade will be between two performance profiles. For example, “better” performance using more power vs. “worse” performance using less power. This is a very common trade in industry.

To achieve the two profiles, a modular approach will be used to swap out blocks for either “better” or “worse” performance. This is the elegance of a modular approach to system architecture. If a parallel effort could be taken to create a corresponding cost model for each block, then as blocks are swapped in and out for performance trades, a cost trade could simultaneously be performed.

As with system modeling, there are several COTS cost tools which may do similar functions. For costing the system in this research, the software package utilized was selected because it contains all the elements required to enable a user to create a modular cost model. Blocks can be created and turned on and off to simulate substituting one block for another. For each cost model block, there are parameters which can be adjusted to influence cost. Those parameters correspond to various ranges of hardware design details ranging from a very high level of detail to a very low level of detail depending on the user’s familiarity with the hardware being modeled. All of the cost data within the COTS tool is pulled from industry standards, so no cost data *needs* to be loaded. Of course, for any user the tool data can be modified for specific applications and past performance actuals. Some cost tools include information regarding the sensitivity of a particular parameter being adjusted. The presentation of the sensitivity factors is currently a bit crude, but it should be possible to pull the data for further analysis outside of the tool.

A. Cost Modelling Approach.

Unlike the system tool structure which focused on artifacts and a manner by which to organize them (See Table 1), a cost tool focuses on the hardware, or more precisely, the indentured organization of the hardware. This allows a system architect to utilize the WBS numbering system directly in the tool. The tool directly estimates cost based on what hardware will be included. So, to create a cost model a user needs to first consider the indenture of the hardware.

Level 1 – Deliverable hardware

Level 2 – 1st Sub-block of hardware

Level 2 – 2nd Sub-block of hardware

Level 2 – 3rd Sub-block of hardware

Etc.

B. RADAR System Cost Modelling Structure.

As with the system model, an indentured set of numbers was created for this system cost model and appears in Table 3. The entries in Table 3 are very similar to those from Table 2. However, Table 3 has additional rows for "Roll Up." A cost tool could call out Level 2 hardware, for example an antenna. However, an antenna is also a collection of Level 3 hardware blocks. In this case, both options are included in the cost model. And when the model is run to produce an estimate either, but not both would be selected.

C. RADAR COTS Cost Model.

The RADAR system demonstrated earlier as a robust set of block diagrams and system model can be loaded into a COTS cost estimation tool. With the structured approach, the numbering and indenture of the entries should remain consistent with that presented in the earlier sections of this paper (Table 3).

As part of the COTS tool, each sub-block contains functional parameters which can be tuned for the specific application. For example, the weight of the specific hardware sub-block could be modified. What is initially loaded is an industry standard value to be used as a starting point.

This is the domain of the cost analyst. A good cost analyst having participated early in the design life cycle of the product will have familiarity with the WBS and product requirements. With a robust cost model which mirrors the system model a cost analyst is well positioned to generate a robust cost estimate and can rapidly participate in trade study alternatives. Because of the modular nature of the model structure, it is

Level 1	Level 2	Level 3	Block Name
001			Radar
	001.01		Antenna
		001.01.01	Radiator
		001.01.02	TR Product
		001.01.03	Duplexer
	001.02		Transmitter
		001.02.01	Power Amplifier
		001.02.02	Up Converter
		001.02.03	Local Oscillator
	001.03		Synchronizer
		001.03.01	Synchronizer
	001.04		Receiver
		001.04.01	Low Noise Amplifier
		001.04.02	Down Converter
		001.04.03	Local Oscillator
		001.04.04	IF Amplifier
		001.04.05	Filters
		001.04.06	2nd Down Converter
		001.04.07	2nd Local Oscillator
		001.04.08	Detector
		001.04.09	Analog to Digital Converter
	001.05		Processor
		001.05.01	Processor
	001.06		Power
		001.06.01	Transformer
		001.06.02	Rectifier
		001.06.03	Filter
		001.06.04	Regulator
	001.07		Display
		001.07.01	Video Amplifier
		001.07.02	Display

Table 3 Indentured Cost Numbering Structure.

possible to turn blocks "on" or "off" to select what is to be included for an estimate. In this way, blocks can be swapped in a modular fashion allowing a cost analyst to work with the system architect the ability to perform cost trades.

VI. Multivariable Analysis & Trade Studies

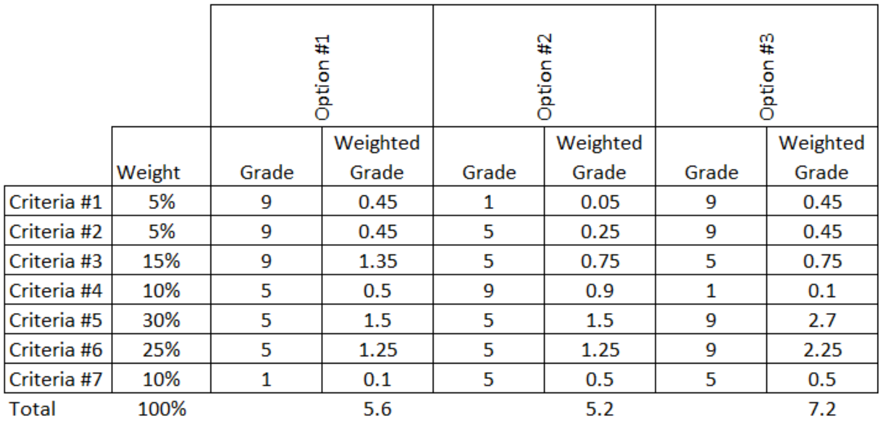
A robust structured system modelling approach utilizes the concept of modularity. If the system is comprised of modules, then the possibility exists where modules could be swapped to modify the system for various performance characteristics. At the same time, if the cost model mirrors the system model, then as the system is being defined, a rough cost estimation could be determined simultaneously.

Even with a modular approach, when designing a system more than one variable must be considered. Choices are made regarding those variables. In most cases, variable choices have competing impacts. For example, one design architecture may have "better" performance using more power vs. "worse" performance using less power. Decisions for a sub-system need to be evaluated at a system level. A system designer needs to consider the design as a system and realize that any change potentially has an impact beyond the sub-system. It is not usually possible to make an architecture or hardware change irrespective of the larger view of the system. This is really the heart of system engineering, consideration of an entire system, not just a collection of sub-system parts.

This is particularly important when considering cost because it is not possible to swap out cost as modular blocks and estimate new costs without understanding that there are affects to the system. There are multilevel impacts when modular blocks are substituted. Simply swapping out a block and estimating cost gives a first order indication of the cost impact. But until the design is finalized it is only a rough estimate. There is a spiral approach to design. As choices are made, impacts are assessed, costs can be estimated, new choices are made, and eventually the design spirals into a solution.

To decide between competing variables a trade study can be employed. A trade study is a useful tool which allows a designer to compare and contrast the various possible choices to determine which solution would be "best" for the given application.

To perform a trade study, first the various options are clearly defined. Criteria must be selected. Criteria are the items which are impacted by the options. Typical criteria are cost, schedule, performance, supportability, etc. A matrix is made with the options vs. the criteria, Table 4. A grade is given in the matrix for each criterion and option. Then the criteria are assigned a weight. The grades are scaled by the weighting factors. And then a score for the options can be calculated by adding up the weighted grades for each option. The option with the highest score "wins" the trade study and represents the "best" solution.



		Option #1		Option #2		Option #3	
	Weight	Grade	Weighted Grade	Grade	Weighted Grade	Grade	Weighted Grade
Criteria #1	5%	9	0.45	1	0.05	9	0.45
Criteria #2	5%	9	0.45	5	0.25	9	0.45
Criteria #3	15%	9	1.35	5	0.75	5	0.75
Criteria #4	10%	5	0.5	9	0.9	1	0.1
Criteria #5	30%	5	1.5	5	1.5	9	2.7
Criteria #6	25%	5	1.25	5	1.25	9	2.25
Criteria #7	10%	1	0.1	5	0.5	5	0.5
Total	100%		5.6		5.2		7.2

Table 4 Sample Trade Study Matrix.

VII. Sensitivity Analysis Applied to a Cost Model

The limitation of the commercially available cost estimation packages is that it is essentially a unidirectional process. A user defines a system and uses the cost estimation package to estimate cost. The user can then experiment with alternatives or modifications to the system and estimate the corresponding associated system cost. What is missing is a bidirectional interaction with the software package. There is very little guidance from the cost estimation package which suggests to the user system modifications for consideration. It lacks suggestions to the designer which modifications would have the greatest impact to the overall cost of the system.

It is desirable to have a feature within a cost estimation package which can analyze the components of the system to determine which components have the greatest impact. In other words, which components have the highest sensitivity for modification as it pertains to the overall cost of the system.

Although sensitivity analysis is well understood the application of sensitivity analysis upon a cost model for the purposes of maximizing the impact to the overall system cost is novel. It should be possible, and is explored in a follow-on paper, an effort to generate a cost sensitivity algorithm of the various components in a system to analyze a system and determine which subsystem components in a chosen design solution have the highest sensitivity to cost for the overall system. The analysis should highlight the areas to which a system designer could apply focus to reduce the overall system cost early in the life cycle of a program.

A. Sensitivity Analysis Potential.

Lack of adequate cost analysis tools early in the design life cycle of a system contributes to non-optimal system design choices both in performance and cost. A goal is to develop algorithms for an automated tool/approach utilizing cost element sensitivity to enable a system designer the ability to understand the relative cost impacts of various decision/choices which affect system design early in the design cycle for an airborne based RADAR system for military aerospace applications.

Most cost estimations are a unidirectional process. First a design is selected then the design cost is estimated. If the cost is not good the only feedback is typically to “reduce” cost. Then a new design is chosen, and the design cost is again estimated. But typically, the process lacks meaningful feedback which demonstrates how or where to make design changes to impact cost most significantly. Instead, the designer typically modifies an area of particular interest to the designer.

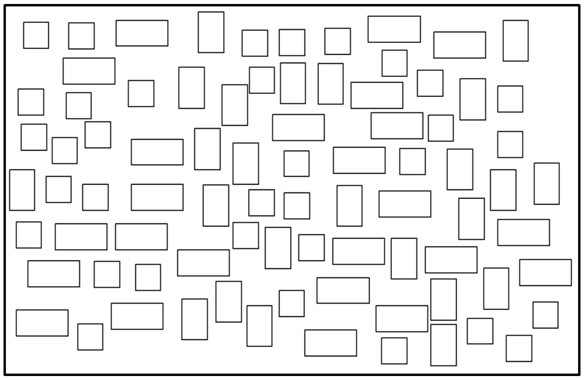


Figure 13. Complex System of Sub-System Blocks.

Consider a complex system made up of sub-system blocks, Figure 13. To estimate the cost of the entire system, the cost of the sub-system blocks is estimated and then rolled up into the top-level system cost. Typically, the cost is too high and there needs to be some effort to reduce the overall cost. So, trade studies are performed which focus on specific sub-system blocks. Of course, if any given block is modified, there will be an effect on other blocks known as secondary effects. For example, “better” performance using hardware which requires more power vs. “worse” performance using hardware which requires less

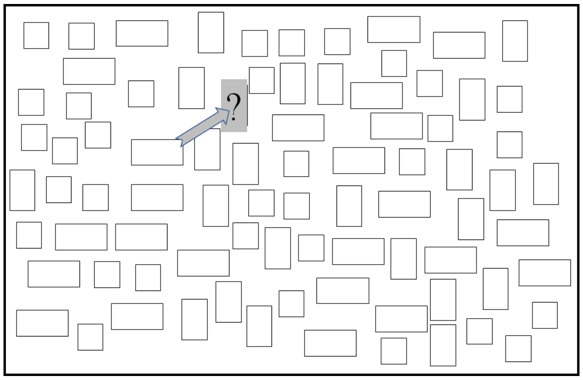


Figure 14. Arbitrary Sub-Block Selection.

power. A change such as that may have a secondary effect of increased copper thickness on other printed wiring boards which would then increase costs in other areas of the design. The secondary effects must be dealt with and considered but that would occur later in the process when a trade study is performed. Initially, there is the challenge of trying to determine which sub-block to apply focus to impact cost most significantly for the entire system, Figure 14. This is where the tools are significantly lacking. In the absence of sophisticated tools, the selection becomes somewhat arbitrary. It is desirable for the cost analyst to actively participate with the system designer to identify the areas of focus where the greatest impact to overall cost could be achieved.

Used in conjunction with a COTS cost estimation tool, it should be possible to develop an algorithm to understand the system sub-blocks in terms of cost sensitivity to overall system cost. With such an algorithm a cost analyst could analyze a system and determine the relative cost sensitivity for each sub-block.

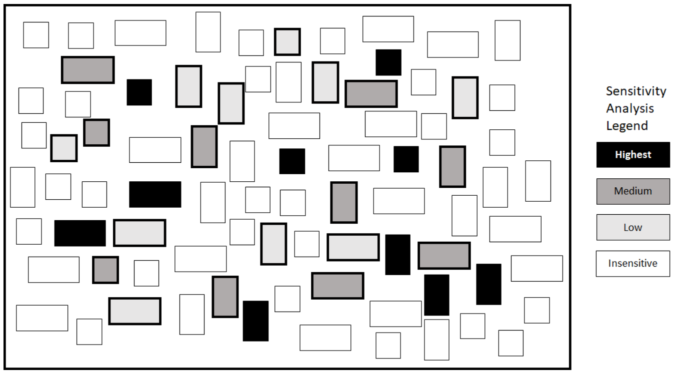


Figure 15. Sensitivity Analysis Results.

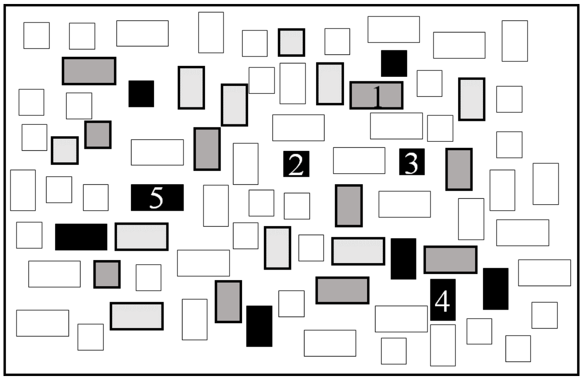


Figure 16. Selection of Five Sub-Blocks.

Once the sub-system blocks have a relative sensitivity value, the sub-blocks could be ranked from most sensitive to least sensitive, Figure 15. Then using knowledge of the system, a cost analyst could suggest a few sub-blocks to focus attention for reasonable improvement goals, Figure 16.

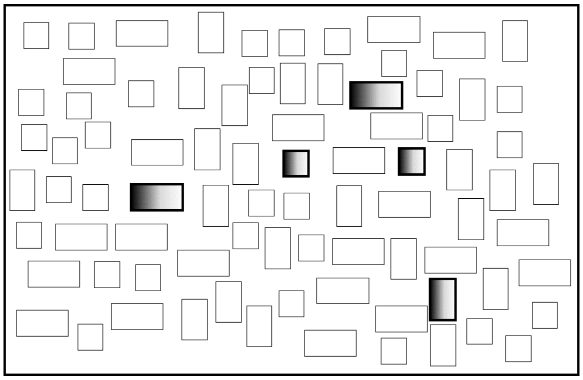


Figure 17. Simultaneous Modification of Five Sub-Blocks.

Once a few sub-blocks have been selected for reasonable improvement goals, and using the COTS cost estimation tool, an estimate could be made to determine the impact of cost to the entire system from simultaneous improvements to these few selected sub-blocks, Figure 17.

The overall impact estimation would provide a bound, or maximum, for potential cost improvements. To realize any potential component cost improvements there would need to be some amount of investment of resources. Any investment up to the estimated maximum potential value would yield a profit. This then forms the basis for a Return On Investment (ROI).

Again, a full trade study would need to be performed to evaluate the potential impacts to the rest of the system. But those trade studies would be paid for using the ROI estimations.

The limitation of the commercially available cost estimation tools is that it is essentially a unidirectional process. A user defines a system and uses the cost estimation package to estimate cost, Figure 18. What is missing is a bidirectional interaction with the software tool. By performing a sensitivity analysis upon the cost model, a cost analyst can offer suggestions to the system designer where to focus attention to most significantly impact overall system cost.

VIII. Summary

This paper presents an approach to generating a set of block diagrams for describing a standardized modular RADAR system applied to military applications in the aerospace industry. The resulting block diagrams were created using a compilation from a wide sample of available industry data and references integrated into a higher level, more generalized version. In addition to block diagrams, generalized block descriptions were also created along with a generalized numbering structure.

This paper demonstrates an approach to implementing the generalized block diagrams and numbering structure to create both a system model as well as a cost model for the RADAR under consideration. By means of the numbering structure, the system and cost models could be generated in such a way as to be modular to facilitate eventual trade studies for performance and cost improvements.

This paper discusses the potential advantages of a cost sensitivity algorithm applied upon the system cost model to analyze and determine which subsystem components in a chosen design solution have the highest sensitivity to overall cost. This paper illustrates that such an analysis could direct system designers to the areas of focus to most significantly impact the overall system cost early in the life cycle of a program.

Finally, the paper discusses using the sensitivity analysis results to select a few sub-blocks for reasonable improvement goals for simultaneous improvements. Simultaneous improvements to these few selected sub-blocks would provide a bound, or maximum, for potential system cost improvements. Any investment up to the estimated maximum potential value would yield a profit. This then forms the basis for a Return On Investment (ROI). The ROI estimate would in turn fund future trade studies.

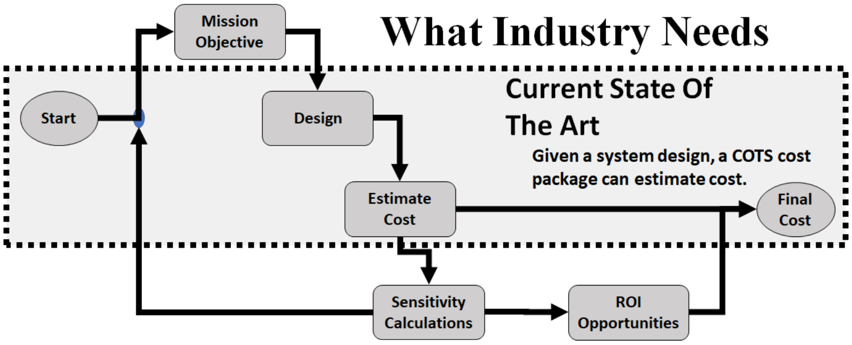


Figure 18. Ideal Cost Estimation Process.

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