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INTEGRATING SYSTEMS ENGINEERING INTO THE USAF ACADEMY CAPSTONE GAS TURBINE ENGINE COURSE

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ABSTRACT

This paper is intended to serve as a template for incorporating technical management majors into a traditional engineering design course. In 2002, the Secretary of the Air Force encouraged the USAF Academy to initiate a new interdisciplinary academic major related to systems engineering. This direction was given in an effort to help meet the Air Force's growing need for "systems" minded officers to manage the development and acquisition of its ever more complex weapons systems. The curriculum for the new systems engineering management (SEM) major is related to the "engineering of large, complex systems and the integration of the many subsystems that comprise the larger system" and differs in the level of technical content from the traditional engineering major. The program allows emphasis in specific cadet-selected engineering tracks with additional course work in human systems, operations research, and program management. Specifically, this paper documents how individual SEM majors have been integrated into aeronautical engineering design teams within a senior level capstone course to complete the preliminary design of a gas turbine engine. As the Aeronautical engineering (AE) cadets performed the detailed engine design, the SEM cadets were responsible for tracking performance, cost, schedule, and technical risk. Internal and external student assessments indicate that this integration has been successful at exposing both the AE majors and the SEM majors to the benefits of "systems thinking" by giving all the opportunity to employ SE tools in the context of a realistic aircraft engine design project.

INTRODUCTION

Perhaps the pinnacle of academic learning is having students accomplish what is expected of professionals in their field. Additionally, by applying professional processes, the course authenticity increases. (1) In 2002, the Secretary of the Air Force encouraged the USAF Academy to initiate systems engineering (SE) and system engineering management (SEM) majors. These majors were integrated into the capstone engineering design courses to make for a richer and more realistic design experience. Currently, the gas turbine propulsion capstone design teams incorporate traditional engineering design techniques, while SEM cadets simultaneously provide structured technical management. This additional oversight comes in the form of managing cost, schedule, performance, and risk. These elements are the same ones balanced during major defense acquisition programs. The tailored SEM curriculum provides SEM cadets with the tools to help the team make justifiable decisions. This realistic environment keeps all cadets aware of the many key issues involved with engine design beyond just achieving a particular technical specification: requirements must be well defined and tracked; trade-offs must be considered, resolved, and defended; interfaces and configurations must be controlled and documented; and risks must be identified, weighed, and have appropriate mitigations.

This paper documents the system engineering management processes and products as they map to the engine design process. First, the activities that professional system engineering managers must accomplish are presented and mapped to previous SEM coursework. Second, these same activities are mapped to the engine design process used in the capstone course. Third, each of these activities is defined, given an engine related example, and tied back to its usefulness in the overall design process. This paper should assist other capstone design instructors as they consider ways to better integrate systems engineering topics.

NOMENCLATURE

AE483- Propulsion capstone course
CA- Constraint Analysis
CCD- Configuration Control Document
DAU- Defense Acquisition University
DID- Data Item Description (milestone briefing)
EPA- Engine Performance Assessment
ICD- Interface Control Document
M- Mach
MA- Mission Analysis
OPR- Overall Pressure Ratio
PCA- Parametric Cycle Analysis
PLA- Power Level Angle
P_t- Total Pressure
RFP- Request for Proposal
RTM- Requirements Traceability Matrix
SE- Systems Engineering
SEM- Systems Engineering Management
SEMP- Systems Engineering Management Plan
SFC- Specific Fuel Consumption (uninstalled)
SPRDE- Systems Planning, Research, Dev, & Engineering
SYS101- DAU Fundamentals of SPRDE
SYS202- DAU Systems Engineering Management
SYS492P- SEM course code for propulsion capstone
TM Technical Management
TSFC-Thrust Specific Fuel Consumption
T_t- Total Temperature

MOTIVATION

System level decisions have been a part of gas turbine engine design from the very first working prototype. In the late 1930’s and early 1940’s, the gas turbine proof of concept and initial production engines employed system level trade-offs to meet customer requirements. In his first demonstration engine, Hans von Ohain recognized the need to prove the capability with hydrogen first. By limiting technical risk of the combustor, he was able to drastically reduce development time. This early success was critical to future development. Even the first axial flow production level engine, the Jumo 004, was purposely designed at a moderate level of performance in order to limit development time, risk, and cost. (2) This heritage provides a touchstone for students embarking on gas turbine engine design using systems thinking.

1 PROFESSIONAL SE PROCESSES

Fortunately, the methods to optimize the system design process have been formalized and documented. From the Air Force perspective, courses available through the Defense Acquisition University (DAU) provide the professional level outline of processes for acquisition management. DAU’s SYS202 course defines Systems Engineering as “An interdisciplinary approach encompassing the entire technical effort to evolve and verify an integrated and total life cycle-balanced set of system, people and process solutions that satisfy customer needs.” (3) This broad definition must be scoped into tangible activities that SEM majors must be able to do within the course. In order to formalize the desired activities for the course, we must consider what skill sets SEM majors require entering the US Air Force. These activities then help build the desired course learning goals from our Air Force customer of future SEM officers.

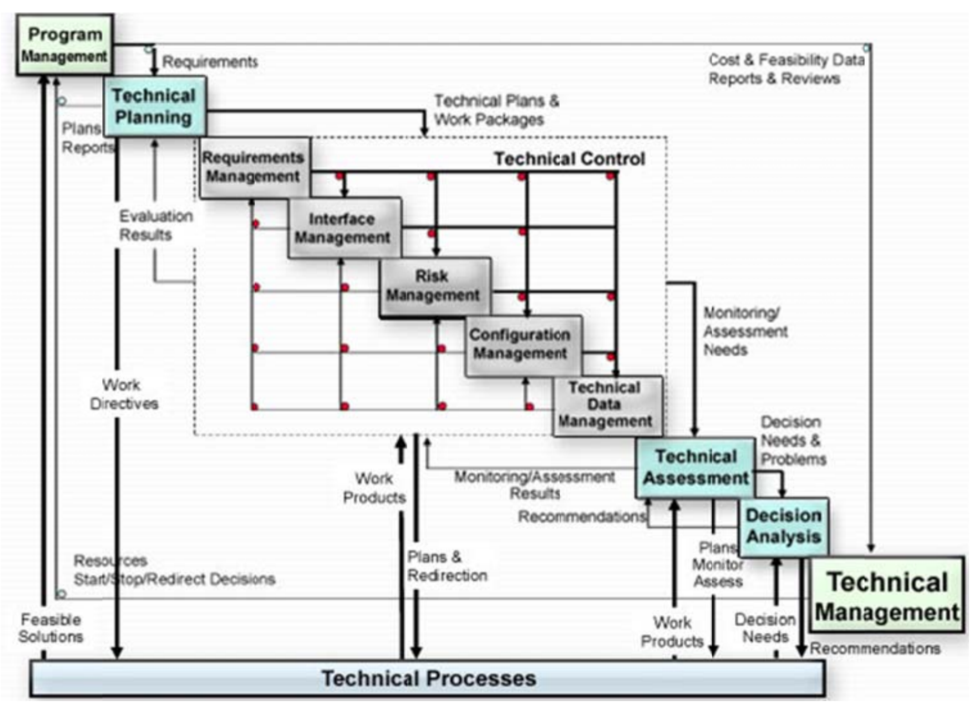


Figure 1. Technical Management Processes Overview from SYS101 Fundamentals of SPRDE (4).

The technical management processes described in the DAU course SYS101, Fundamentals of SPRDE, give a framework for the elements necessary in any design process. Figure 1 shows these processes in a flow chart. These processes work together within an acquisition program. As the figure implies these processes are iterative. Within the technical control block, all processes work together and impact all the others. Therefore any change in one of these requires an additional iteration on all other technical controls. Not as readily apparent, but just as important, system and sub-system level designs require the processes be applied recursively, i.e. at each level.

Table 1 maps the professional processes back to the specific activities and associated assignments in the capstone course. The first column of Table 1 shows the 8 technical management processes outlined in SYS101 and an additional process to model cost. The next two columns show the capstone specific product(s), and the assigned data item description (DID). The DIDs are the calendar driven assignments that act like acquisition progress reviews to assess the program status. The engine design course has 6 DIDs with specific requirements and specific due dates. These will be mapped using the course flow chart in Section 2.

Table 1. Technical Management Processes.

SE PROCESS	ENGINE DESIGN CAPSTONE SEM PRODUCT	DID
I. Technical Planning	1. Systems Engineering Management Plan (SEMP) 1.1 Org Chart; 1.2 Job Definition; 1.3 Gantt Chart	1
II. Requirements Management	2. Requirements Traceability Matrix 2.1 Specified RTM 2.2 Derived RTM	1,2
III. Interface Management	3. Interface Control Document 3.1 Aircraft ICD; 3.2 Thermodynamic ICD; 3.3 Physical ICD	2,3,4
IV. Risk Management	4. Risk Matrix 4.1 Aircraft; 4.2 Thermodynamic; 4.3 Component	2,3,5
V. Configuration Management	5. Configuration Control Document	5
VI. Technical Data Management	6.1 2-D Cutaway 6.2 3-D Drawing	4,6
VII. Technical Assessment	7. Instructor Activity	N/A
VIII. Decision Analysis	8. House of Quality	3
IX. Cost Model (not in SYS101)	9. Cost Model	3,5

These processes can be applied for any set of requirements that will be carried through to final design. Process one, technical planning, sets the stage by planning the people, tasks, events, and corresponding times in a schedule. Processes two through six and nine provide technical control as the system is developed. A change anywhere in these processes affects the others and will require iteration. Changes must be tracked and documented as to why the change was made using interface and configuration control documents. The technical assessment, process seven, lets the design team know how well it is performing. Finally, process eight, decision analysis, is used to objectively weigh alternative solutions and make justifiable decisions.

2 ENGINE DESIGN PROCESS & SEM ACTIVITIES

The engine design process provides the context for all of these SEM activities in the propulsion capstone. The course text, Aircraft Engine Design, (5) provides a flow chart of the engine design process. Figure 2 shows a simplified version of this design process where a rough time-line starts from the top to bottom. The left column shows the DIDs which represent calendar driven reviews. The middle section shows the engine design process, which is roughly broken up into three parts. First, cadets assess the system level interactions to determine engine performance requirements. Second, the team builds a working thermodynamic engine model that meets mission requirements with a first-order aircraft model. Finally, the team designs the components required to achieve the required thermodynamic model properties. The right hand column shows the SEM associated product from Table 1, column 2, for that particular DID.

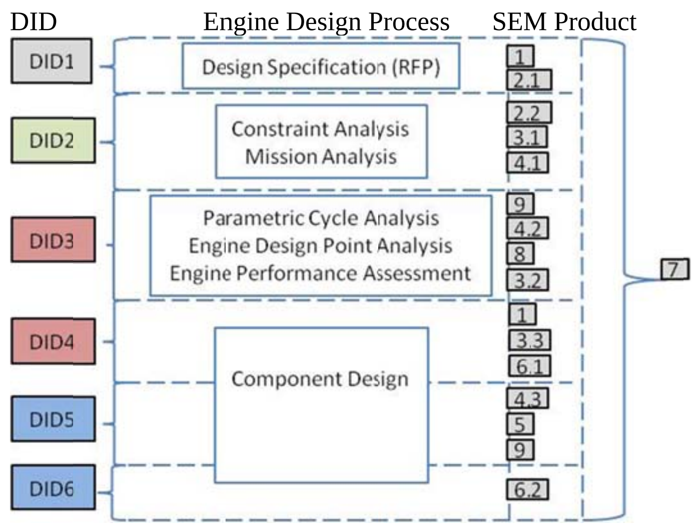


Figure 2. Design Process from Aircraft Engine Design.

The process starts by receiving the RFP, through constraint and mission analysis, thermodynamic analysis, through component design. Like the technical management processes described above, this engine design process is also highly iterative and recursive. Fortunately, these simultaneous processes, engine design and technical management, can be overlapped. By notating the SEM products from Table 1 to the corresponding engine design activity, there is a single road map for the course. This map ensures that both disciplines are aware of the appropriate activities to conduct at any point in the semester.

Each of the activities in Table 1 is aligned in Figure 2. All SEM products are developed by SEM cadets except the technical assessment; this is conducted by the instructor. Normally technical assessment would be conducted using a tool like earned value management. (6) This tool helps a program office or contractor determine the total technical progress of the program. However, for the engine design course, this particular activity is conducted by the instructors through regularly assigned briefings and feedback sessions. In this context the instructor acts as a coach or overall team-lead. This instant assessment and feedback lets the instructor and team know the state of progress throughout the semester.

The data item description or DID is a calendar driven review that ensures appropriate progress at specific points in the semester. Each DID assignment provides specific detail for requirements for that particular briefing. It includes point values for each item required and exit criteria for the team to advance to the next stage in the design process. All SEM and engineering activities culminate in a briefing for each DID. All DIDs coincide for SEM and engineering students except for DID 3 which will be discussed in Section 2.3. Each of the next six sections will outline what the engineering activity is for that particular DID followed by the corresponding SEM activity.

2.1 Data Item Description 1

DID 1 establishes the Systems Engineering Management Plan (SEMP) for the semester. All engineering and SEM cadets are involved in this activity. There are no separate engineering activities for this effort. All cadets are engaged in organizing the team and understanding the RFP.

Figure 2 shows that for DID 1, the SEM products are the SEMP and specified RTM, i.e. products 1 and 2.1 respectively. The first process, technical planning, requires taking the RFP, determining the desired end state, the tasks required that must be accomplished, and the schedule to reach that final objective.

Concurrent with technical planning, SEM majors and engineers scrub the RFP for specified customer requirements. In order to trace technical specifications back to customer requirements, SEM cadets employ activity 2.1, building a specified requirements traceability matrix (RTM).

2.2 Data Item Description 2

DID 2 establishes the engine performance requirements based on a system analysis of the integrated aircraft/engine platform. The engineers use empirical engine and aircraft models through constraint and mission analysis to determine engine performance requirements. During DID 2, the engineers present the thrust-loading and wing-loading as well as the required fuel, thrust, and thrust specific fuel consumption (TSFC) for each mission leg. From this analysis, cadets also select the design Mach and altitude.

The corresponding SEM products for DID 2 in Figure 2 are 2.2, derived RTM; 3.1, Aircraft ICD, and 4.1, Aircraft Risk Matrix. The SEM cadets brief each of these products for their portion of DID 2. The derived requirements are the result of a detailed mission development that matches the. These derived requirements are updated in the RTM by the SEM cadets. This becomes a checklist for validation of the final design. Does the aircraft have enough fuel to complete the mission? If the answer is “yes” the design can work, otherwise, further iteration is required.

The second product results from interface issues. The SEM students track interface issues with the parallel aircraft design capstone. The interface issues are managed using an interface control document. The same difficulties encountered in industry must be addressed. How big is the nacelle? What is the drag polar? What is the required thrust loading and wing loading? All of these issues must be considered and agreed upon. It is the SEM cadet’s responsibility to control interface issues with each new baseline, tracking changes and reasons for changes.

The final product is the aircraft level risk matrix. Even though the engine at this point is an empirical model, the choices for this model rely on a judgment of technical risk. For example, if the turbine inlet temperature sought is aggressive it must be noted, weighed and given mitigation options.

2.3 Data Item Description 3

DID 3 establishes the thermodynamic model to be used through the rest of the course. Engineers parametrically examine many different cycles. After much iteration, the engineers select a cycle for further study based solely on performance. The engineers brief how this engine will perform on and off design as well as the mission impact. This briefing occurs several days before the corresponding SEM major’s assessment, and provides the baseline for SEM examination.

The DID 3 assignment for SEM cadets is the only separate briefing during the semester. The SEM cadets fully assess the thermodynamic engine selected by the engineers. With engineering help, the SEM major will examine the impact to performance of increasing and decreasing T_{t4} by 5%. Then the SEM cadet can apply system engineering tools to examine each of these three engines in terms of risk, cost, and development schedule. They perform a decision analysis to determine whether the cycle selected is the best considering lifecycle costs and impacts on things like maintainability and survivability.

The SEM majors also publish the thermodynamic interface properties between engine stations, namely total temperatures, total pressures, Mach numbers, and mass flow rates. Every component designer must know what the entrance and exit conditions are for his/her component. This interface control document will help keep the team in check. For DID 3 this is only done for the on-design condition, but becomes the template for future efforts. The reason for only publishing on-design values at this point is economy of effort. If the instructor sees a need to further iterate, the team can develop a new thermodynamic cycle without the loss of a large time investment.

2.4 Data Item Description 4

DID 4 establishes the thermodynamic model for all mission legs and the plan for component design through the end of the semester. Engineers provide the engine station properties at every mission leg through a simulation. This simulation shows the aircraft condition (Mach, altitude, and weight), engine throttle hook and power lever angle (PLA), and internal engine properties at each leg. Additionally, a nominal 2-D drawing of the engine flow-path provides a means of technical data management. The SEM majors re-examine the organization, schedule, and tasks required to meet milestones through the end of the semester.

Once the team has selected the thermodynamic cycle for further study and received instructor approval, it must now plan for component design. Engineers break into smaller component design teams. They will build a detailed simulation of the mission which shows aircraft properties, engine properties, and component thermodynamic properties at every mission leg. They will also brief their plan through the end of the semester for their component.

The SEM cadets conduct all of the planning activities in process one, technical planning, through the end of the semester. Additionally, the simulation built with the engineers becomes the detailed component interface control document. This includes the thermodynamic properties previously tracked, but now also includes the required areas at each station.

With a first estimate for hub radii, the entire 2-D engine flow path is presented as a baseline. This 2-D drawing with hub radii and tip radii at every location and an initial estimate for rotor angular velocities is the baseline component-level interface control document. This document allows the inlet designer to have the same target exit Mach as the fan designer has for entrance Mach. Additionally, the flow path should not have sharp turns when moving from the fan to the compressor. Component designers are expected to negotiate changes, but any updated property must be controlled and documented. A 2-D drawing at this point is quicker to produce than 3-D, which is desired due to the probability of multiple iterations.

2.5 Data Item Description 5

DID 5 provides the first review of the component design. Once the SEMP from DID 4 has been set, the rest of the semester is involved in individual component design, performance assessment, sensitivity studies, analysis of alternatives, and final decisions on physical shape and materials of each component. These efforts go through much iteration, but with a frozen thermodynamic engine. At this point in the semester, even if making a new cycle selection is attractive, it is documented as a recommended future effort due to time constraints.

At DID 5, the SEM cadets assess component level risk. Any exception to published constraint values must be noted, weighed and mitigated through risk assessment. Is the rotor speed low enough that the engine avoids tip shocks? If not, its risk must be assessed. A mitigation plan could include proposing funding for 3-D computational fluid dynamics analysis using swept blades to mitigate flow separation. Second, the SEM cadets reassess the cost model with better fidelity numbers for engine size and weight. Lastly, SEM cadets assist with configuration control so that component designers can well document the reasoning for their final component design. Such decisions must balance trade-offs with well-documented explanation. More uniform burning and temperature distribution can be achieved in a combustor with twice the number of swirlers, but what about cost, complexity, and supportability. In order to justify the final decision a bigger “systems” level picture must be taken into account. As each component designer down selects to a particular design, that selection process should be rigorously achieved through decision analysis.

2.6 Data Item Description 6

DID 6 establishes the final component design. The engineers have completed designing their component. They must present the final design and provide rational explanation for the design through figures and analysis of alternatives.

The SEM cadet effort for DID 6 is to assist with the overall presentation effort including the SEM story of the engine selection. The SEM majors also continue the technical data management by assisting with the 3-D engine cutaway drawing. This final in-class presentation should be the dress-rehearsal for briefing industry experts at the end of the semester.

3 ACTIVITY DEFINITIONS AND ENGINE EXAMPLES

Now that the system engineering activities have been mapped to the engine design process, specific examples and descriptions for the engine design capstone will be used to illustrate the steps in the process. The order of activity definition corresponds to the order shown in Table 1.

3.1 TM Process 1: Technical Planning

The first process, technical planning has several potential products. Typically, a work breakdown structure would examine every detail of the tasks that must be managed. (7) A similar process occurs for the course, but because of the small team size and scope, can be accomplished more succinctly. The SEMP is accomplished through 3-tiers, each containing greater levels of detail. First, an organizational chart sets high level areas of responsibility. Second, detailed job descriptions further define specific duties. Finally, a detailed Gantt chart outlines lower level tasks against a time-line with critical milestones and parallel efforts displayed.

Figure 3 shows an example organizational chart broken into two parts. The first effort, part 1, takes cadets from RFP through DID 3, roughly half of the course. Once the cadets have frozen the thermodynamic design, the part 2 chart presented during DID 4 provides the organization through the end of course. The organizational charts provide a quick glance of work breakdown that keeps everyone in the class, including instructors aware of individual responsibilities. The key attributes are cadet names, areas of responsibility, and lines of communication. Another critical feature is that all parts of the design process and all engine components must have an owner.

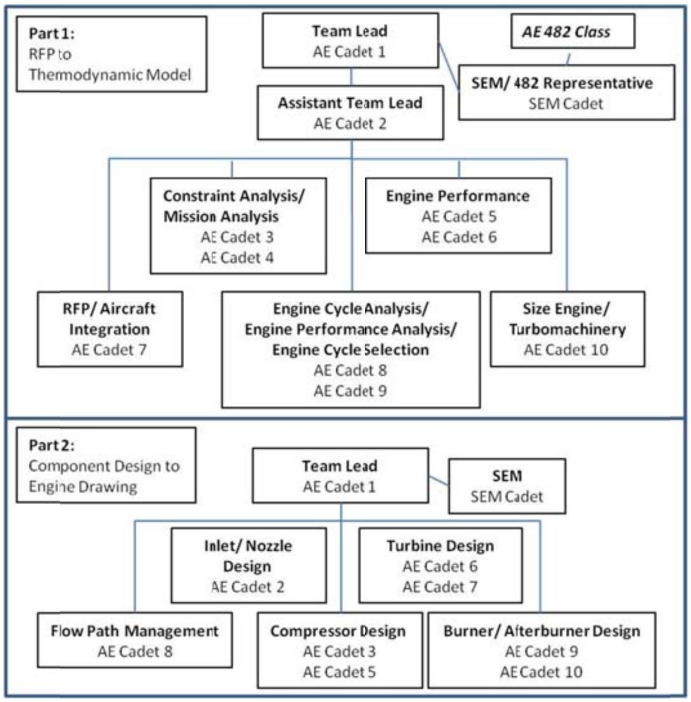


Figure 3. Organizational Chart, top-level WBS.

The second level activity presented during technical planning is defining the job descriptions. Once the areas of responsibility have been assigned, each cadet provides a detailed description of his or her responsibilities. This one or two slide presentation from each cadet should have a bottom line up front description of what his/her job must contribute to the design effort. Key elements for the job description are required inputs, outputs, assumptions, procedures, and interface issues. It should be clear that every cadet knows how they fit into the overall design process. Once each cadet has researched and articulated his or her efforts, the team can lay out a detailed plan for achieving each milestone.

The detailed level of effort down to timed individual tasks occurs through the Gantt chart. Other techniques are available such as the critical path method, but the Gantt chart contains the appropriate level of detail to ensure success for the course, without excessive effort.(7) For this course, Microsoft Project is the required tool for developing the chart. The key elements of the Gantt chart are the broken down tasks, schedule with major milestones, and bars showing schedule and duration of activities for each task. As part of the briefing on the planned schedule, cadets must notate any critical path issues. An example is the requirement to have a defined drag polar before beginning the system level performance investigation, ie constraint and mission analysis. For such a potential bottleneck, cadets must have a plan for moving forward. To limit the drag polar decision as a pitfall, the engine team should have a drag polar expert. Additionally, the team should show the plan for parallel work if the drag polar decision is delayed.

Technical planning is critical to the success of the engine design process. Building a SEMP for the course will ensure that cadets have a clear path forward and can manage the complex design process effectively. The planning of the course itself would not be possible without this level of integration.

3.2 TM Process 2: Requirements Management

The second activity in Table 1 is requirements management. The product used is the requirements traceability matrix. The SEM majors alongside the engine design teammates fill out and maintain a Requirements Traceability Matrix (RTM). The RTM is a systems engineering document that describes the allocation of system requirements to lower levels within the system (8). It is useful for keeping track of both the specified and derived system requirements and serves as a checklist by both the cadets (as members of the design team) and the instructor (who plays the role of a government contract manager). The specified system requirements are found in the "Request for Proposals" and include such items as aircraft mission leg information (altitude, Mach number, endurance, range, and payload). The derived system requirements emerge during the aircraft and engine design process and include such items as minimum thrust loading, maximum wing loading, gross takeoff weight, maximum TSFC, minimum specific thrust, etc. These requirements provide the framework for determining the range of workable cycle parameters during parametric cycle analysis (PCA) and engine performance analysis (EPA). Once the cycle parameters and the engine is sized, RTM's are then used for each component to keep track of the derived system requirements imposed by PCA and EPA. A review of the RTM at both intermediate and final preliminary design reviews is intended to demonstrate that the team successfully kept track of and achieved the system requirements.

3.3 TM Process 3: Interface Management

The third technical management process is interface management. Interface management is conducted using interface control documents. There are three levels of interface management that occur at different points in the engine design process. These are at the aircraft, thermodynamic, and component levels.

Table 2 shows an example aircraft interface control document for a change in one parameter. The key attributes of this ICD are the technical parameter, its current value, approval date, reasons for change from the baseline and current computer model designation. In the example, the engine team realized after a first iteration that it could provide the necessary thrust at all mission legs with a smaller inlet by using blow-in doors during take-off. This decreased area at station 1 meant that the nacelle could have a smaller diameter, decreasing the profile drag. This new information required an update to the baseline through constraint and mission analysis. By book-keeping, the entire team knows that there is a new computer model, M2_14Jan.aed, which is the new baseline. This aircraft ICD is a shared document with the aircraft design team and any changes must be approved by both teams. Occasionally

Table 2. Aircraft Interface Control Document Sample

Parameter	Value	Date	Reason	Impact	File
Nacelle throat diameter, (Dt)	52 in	10Jan	Baseline		M1_10Jan.aed
Dt	48 in	14Jan	Decreased drag **(**C_{D0}) while still enough mass flow rate	(-) C_{D0} (-)W_{fuel} Re-do CA, MA	M2_14Jan.aed

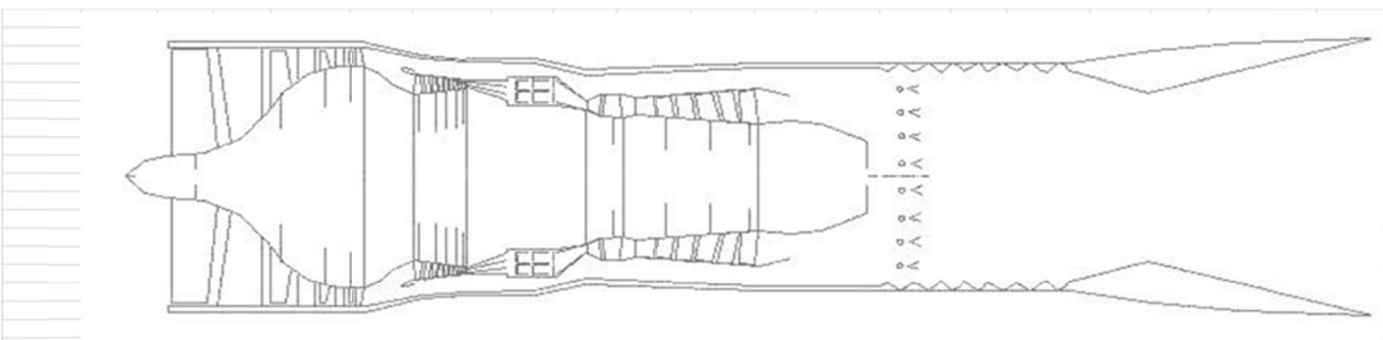
requests for changes to threshold or objective values in the RFP are made. These are decided by the instructors, but must also be documented in the ICD.

Figure 4 shows an example of this large wall chart. During the build up to DID 3, this wall chart is posted for regular reference by all team members. The chart has top and bottom halves. At the top is a nominal 2-D cutaway drawing of the engine showing the flow path and station numbers. The bottom half is a table with each station number as a column and thermodynamic and physical sizing numbers as the rows. The properties to be tracked are total temperature, total pressure, Mach number and mass flow rate for the thermodynamic baseline. Additionally, the physical size values are the annular area, hub radius, tip radius, and low and high shaft angular velocities for the component baseline. In this instance any change from the baseline requires a completely new figure. As part of the tracking process, the new wall chart must document the date, reason for the change, and new model number.

As an example, if the team decided during the development of its thermodynamic model that a higher overall pressure ratio (OPR) would be required, it would have to have a new thermodynamic wall chart. On the chart it would have the date, 22Feb, reason for the update, higher OPR, and the descriptive name of the new engine file, E2_32OPR_22Feb.ref.

The ICD for the thermodynamic and component levels has a different format.

The thermodynamic ICD is conducted by DID 3. The more detailed component ICD must have interface values at all mission legs. This means a table, similar to that in



	free stream	inlet	fan face	begin bypass	end of LPC	begin burner	internal burner		turbine inlet
	station 0	station 1	station 2	station 13	station 2.5	station 3	station 3.1	station 3.2	station 4
M dot(lbm/s)	269	269	269	269	168.12	168.12	149.63	149.63	155.75
Gamma	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.3
Pt(psia)	6.21	6.028	5.847	34.076	44.052	198.787	198.787	196.799	192.824
Tt(R)	565.46	565.46	565.46	995.77	1073.57	1732.14	1732.14	1732.14	3899.99
M	1.5	0.8	0.6			0.35	0.35	0.06	1
MFP	0.45022197	0.51004	0.44566	0	0	0.29783216	0.297832	0.054784	0.51602653
A(ft^2)	15.8881178	14.4483	17.0471			0.82070829	0.730446	4.011177	0.67883494
Hub (in)									16
Hub (out)						13	13	13	

	internal turbine		begin LPT	exit turbine	mixer	mixer/bypass	mixed	AB	nozzle chokepoint	nozzle exit
	station 4.1	station 4.4	station 4.5	station 5	station 6	station 16	station 6A	station 7	station 8	station 9
M dot(lbm/s)	164.16	164.16	172.56	172.56	172.56	100.88	273.44	273.44	273.44	273.44
Gamma	1.3	1.3	1.3	1.3	1.3	1.4	1.3297	1.3297	1.3297	1.3297
Pt(psia)			90.987	34.076	34.076	34.076	32.752	31.934	31.934	31.295
Tt(R)	3769.43	3230.6	3139.02	2554.01	2554.01	995.77	2066.16	2066.16	2066.16	2066.16
M					0.4	0.386	0.421	0.421	1	2.5371
MFP	0	0	0	0	0.32205	0.323421646	0.339113	0.33911	0.52013529	0.1757295
A(ft^2)					5.51844	2.005877507	7.771394	7.97046	5.196511427	15.6950207
Hub (in)										
Hub (out)										

Figure 4 must be made for each leg. The constraining leg for different parameters should be highlighted. For example, if the acceleration leg requires the most thrust, its table should highlight the largest mass flow rate at station 0 with some explanation.

The importance of this effort cannot be overemphasized and is important to integrate into the course. The clearest impact of not performing proper interface control management would be a final briefing displaying a lack of communication. An example might be if the low pressure turbine and fan designers each briefed different mil power (full throttle nonafterburning) rotor speeds (with no discussion of gear-box design).

3.4 TM Process 4: Risk Management

Process 4, risk management, also has several methods. During SE310, cadets are taught a Paredo chart method. (7) However, during their course project they also learn the preferred method for this course, the probability consequence chart. Figure 5 shows an example of this chart. The key features are the numbered risk items that are being tracked, the item itself, and the mitigation method (not shown).

Figure 4. Thermodynamic ICD (DID 3) Example

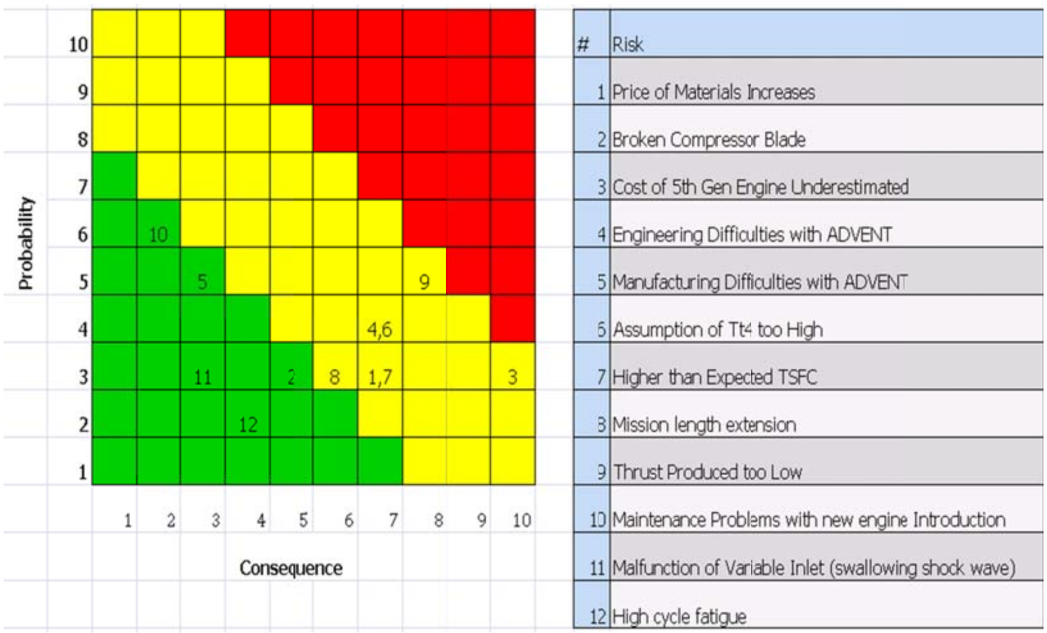


Figure 5. Risk Chart Example.

3.5 TM Process 5: Configuration Management

Process 5, configuration management is slightly different in scope, but with the same objective as interface control management. Interface control targeted external or boundary management. Configuration control targets internal management. In this case a component designer must track the development of his or her component. Although this level of detail is not required for the final briefing, it is important that a component designer can also explain the current status of his or her design and how it evolved.

Key features of a configuration control document should include the physical change(s), performance effect(s), and computer file name.

Parameter	Value	Date	Reason	Impact	Filename
Baseline	Baseline	22 Mar	Baseline	Ψ=0.3 dTt=70degR	B_22Mar.comp
α_1	70deg	22 Mar	+ α_1 10 deg	Ψ=0.35 dTt=90degR	a170_22Mar.comp

shows an example. Here, the fan designer decided to test increasing the flow entrance angle, α_1, by 10 degrees from the baseline, 60 degrees. The new design has an α_1 of 70 degrees, an increased stage loading of 0.35, and total temperature rise of 90 R. By keeping separate computer files for each different configuration, the component designer well organizes the multitude of potential designs into a manageable and useful set.

3.6 TM Process 6: Technical Data Management

The next process, technical data management, also has a multitude of possible tools. For simplicity, the products for this course are a 2-D drawing by DID 4 and a 3-D drawing by DID 6. The 3-D drawing must be built by cadets using Solid Works.

This extra level of effort is the expectation for professionals in the field. It is also expected that some 3-D stereo-lithograph model will be built for demonstration purposes at the end of course briefing.

3.7 TM Process 7: Technical Assessment

Process 7, technical assessment is conducted formally by the instructors through written and oral feedback during each DID. Additionally, informal feedback during class time work sessions helps cadets and instructors understand the current technical status. Key features of technical assessment are clear guidance on the aspects of the design that are on target, those that are off-target, and recommended follow on procedures.

In order to optimize feedback, cadet briefings must be clear and concise. Each presentation should have the big picture bottom line up front. Each slide should be able to stand alone and have a boxed written take-away.

Parameter	Value	Date	Reason	Impact	Filename
Baseline	Baseline	22 Mar	Baseline	Ψ=0.3 dTt=70degR	B_22Mar.comp
α_1	70deg	22 Mar	+ α_1 10 deg	Ψ=0.35 dTt=90degR	a170_22Mar.comp

Table 3. Configuration Control Document: Fan

Not only does this help in understanding the current status, but it provides critical documentation that will be important later in the semester. In other words, when cadets are 2-months into the design, they can return to the DID 2 briefing and see clearly why they decided to use a particular thrust loading.

3.8 TM Process 8: Decision Analysis

Process 8, decision analysis separates a working design from an excellent optimized design. The only formal application of the house of quality is for the SEM major DID 3. However, a logical explanation of trade-offs is required at every level of the design effort. Proper use of sensitivity studies and analysis of alternatives must be shown for every decision from thrust loading at the system level, to fan pressure ratio at the thermodynamic level, to nozzle length at the component level.

An excellent use of available resources in deciding the Thrust Loading and Wing Loading is to plot the cadet design against historical data. Figures 2.2 and 2.3 in Aircraft Engine design each plot thrust and wing loading for many cargo and fighter aircraft respectively. This sanity check proves that the design is in line with historical aircraft having similar missions.

The carpet plot is the tool of choice for selecting design cycle parameters. The parameters to vary are T_{t4}, compressor pressure ratio, fan pressure ratio and bypass ratio. These design choices can be varied two at a time for each carpet plot. Each cycle is then plotted against the uninstalled specific fuel consumption on the y-axis and uninstalled specific thrust on the x-axis. Through system level analysis, cadets determine the maximum allowable TSFC and can determine a reasonable maximum SFC to limit the design space. Additionally, with the thrust requirements and an estimate of size, the cadets can also determine the minimum specific thrust. The maximum SFC and minimum specific thrust limit the design space to the bottom right quadrant of the carpet plot.

The final decisions to make concern component level analysis. The documentation for making these decisions must show variations in geometric choices and their effect on performance. Figure 6 shows an example plot for selecting a particular combustor design. Here the y-axis shows the geometric choice of combustor length, which in this case is determined by exit Mach on the y-axis. This particular compares the effect of using single or dual annular design. From this figure it is clear that the combustor length can be greatly decreased using a double annular design.

3.9 Process 9: Cost Model

The SEM cadets apply the RAND cost-estimating relationships (9) for turbofan engine development cost, development time, and production cost based upon inputs they receive from the AE 483 cadets on their design team. The specific inputs for a new engine with advanced technologies (or a new centerline) are

Rotor Inlet Temperature (deg F)
Overall pressure ratio
Dry engine weight (lbf)
TSFC (1/hr)
Afterburning (yes =1; no = 0)
Full-scale test hours = 6000

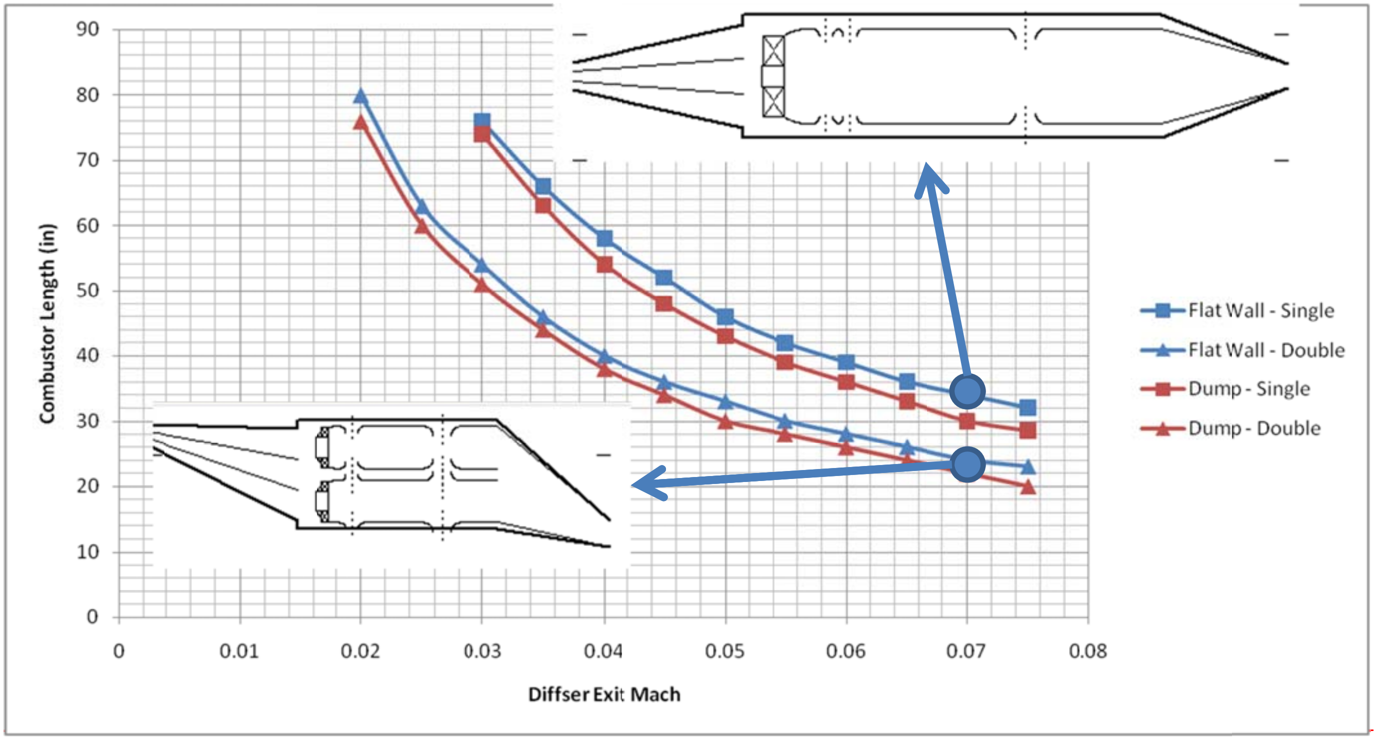


Figure 6. Combustor Analysis of Alternatives Example.

All of these inputs except for dry engine weight and full-scale test hours are obtained fairly early in the semester using parametric cycle analysis. The dry engine weight is estimated later once the engine has been sized. After the engine diameter and axial length have been determined, a rough estimate of dry weight can be found using a volume scaling approach based upon the known dry weight and known volume of an engine in the same class of gas turbine family.

The cost-estimating relationships are based upon a parametric quantitative analysis of historical data on engine costs. The strongest influence on cost and development schedule is the rotor inlet temperature so the cadets get to see the tension and tradeoffs associated with seeking the higher rotor inlet temperatures to obtain greater operating performance. The RAND study points out that the residual error for the development cost and development time estimating relationship is high but they are still useful for weighing trade-offs during the conceptual stage of engine design. The SEM cadet presentation on this topic almost always gets a lot of interest from the industry experts during the preliminary design review.

SUMMARY

This paper provided an overview of the integration of systems engineering management into the engine design capstone at USAFA. The technical management processes, mapping to the engine design course, and specific examples were presented. As SE techniques and engine design processes evolve, the specifics may change. The concept of a managed, multi-disciplinary, integrated course however, is here to stay.

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