# Systems Engineering Thesis Research Methods

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Navy curricula sponsors have consistently told the Naval Postgraduate School (NPS) they want students to write a thesis. A thesis is the final step toward earning the MS degree and establishes a student as a professional able to engage and lead others in technical endeavors. The purpose of this document is to describe what a thesis means in the Systems Engineering discipline.

To start let's define a thesis as *a statement put forward as a premise to be proved based on engineering research*. The NPS proposal asks for a research question rather than a statement, which may be confusing. However, this is a matter of semantics because a research question is nothing more than the thesis statement posed as a question. The definition of a thesis as a statement is useful to guide us because it emphasizes the fact that a thesis is a claim - i.e., the statement made by the author upon which the remainder of the document argues for or against. A thesis writer needs to approach the task from the perspective that he is trying to persuade the reader that a thesis is true or false as the case may be. Importantly, the thesis writer must substantiate the claim with evidence and data generated from the selected research method, critical thinking, and data analysis as appropriate. The thesis is novel in that you are addressing a new problem or claim, or you are approaching an existing problem with a different underlying theory or a different research method. Finally, the thesis statement should be of interest to the larger community including the Navy, defense, and systems engineering communities.

Appropriate topics for a systems engineering thesis can be almost any topic in the systems engineering domain. A thesis can address a particular problem faced by the systems engineering community or a subset of the systems engineering community. A thesis can seek to advance the methods, techniques, or tools used by system engineers. Regardless of the topic, a thesis should advance some small portion of the body of systems engineering knowledge.

The thesis is often a student's most challenging requirement because it is a singular, individual, and student-led effort. The student must identify a thesis topic, determine an appropriate research method, conduct the research, and document it. The timeline is demanding. Importantly, a student must leave sufficient time for iterations of review and feedback from the advisor, second reader, thesis processing office, and department chair. By thinking ahead of time about the nature of the thesis, thinking about the research methods available, and envisioning how you will substantiate your thesis claims, then you are more likely to succeed.

## 1 Engineering Thesis Research Methods

A thesis writer has a choice about the research method where a research method is the means the student uses to generate and/or obtain data, results, and evidence to support the thesis statement. The research method can be experimental, design, empirical study, analysis, or a combination of two or more of these methods. It is via the research method that a student contributes new knowledge to the systems engineering body of knowledge. The following subsections describe each research method.

## 1.1 Experimental Thesis

The experimental approach to a thesis is the most traditional research method in the sciences. The experimental approach essentially applies the scientific method to an engineering question. The thesis statement in an experimental thesis is a hypothesis. The thesis states a hypothesis, examines the relevant literature to motivate the hypothesis, describes an experimental procedure to test the hypothesis, analyzes the results of the experiments, and makes conclusions whether the hypothesis was rejected or not rejected.

Experimental types of thesis are currently rare in systems engineering, but they do not need to be. Here are some illustrative hypotheses to illustrate the use of the experimental approach to many subfields within systems engineering:

- **Model-Based Systems Engineering (MBSE)**: Engineers using SysML Activity Diagrams to model scenarios are able to document more system requirements than engineers using Functional Flow Block Diagrams to model scenarios.
- **Combat Systems**: The material *xyz* can absorb sufficient laser energy to delay damage.
- **Logistics Area**: Rapid prototyping of spare parts on the ship is more effective than alternative spare part policies.
- **System Control**: A unmanned aerial vehicle using *abc* controller leads to more accurate and precise control than a unmanned aerial vehicle using *xzy* controller.
- **Cost Estimation**: The COSYSMO model can better estimate ship costs than current methods.
- **Ship Systems**: A *xyz* hull shape has better sea-keeping ability than a *abc* hull shape.

In the above examples, each thesis statement is specific, clear, and concise. The thesis statements are specific to the particular topic or problem being addressed, they are clearly written so the reader knows what the author sets out to prove, and they are concise since they do have superfluous text or qualifications.

The experiments to collect data to support the thesis statement can be performed with people, laboratory equipment, models, or simulations. For example, the MBSE hypothesis can be tested by having people such as other students use SySML and FFBD to model scenarios. The combat systems example can perform laboratory experiments with a laser. The logistics example can create a simulation model of logistical policies for spare parts. The system control example could fly UAVs with the different controllers. The cost estimation example can compare cost estimations from COSYSMO vice other cost estimation methods. The ship system example can test hull shapes in a tow tank. The point is there are actually many interesting and doable experimental theses in systems engineering.

Experimental thesis can be rather short in terms of the size of the document. The novelty in an experimental thesis comes from the design, execution and analysis of the experiment. The evidence is partially in the form of the results and partially a logical argument that the experiment adequately tests the hypothesis.

## 1.2 Empirical Thesis

Empirical research is based on posing a research question or hypothesis and collecting data from actual projects or engineers to accept or reject the hypothesis. Data collection can be via surveys, interviews, case study, or document collection. The systems engineering discipline is in sore need of empirical research to substantiate whether our processes, models, and techniques are effective, under what conditions are they effective, and to answer many other questions about the practice of systems engineering.

As mentioned, there are countless topics for empirical research. As one example in the subfield of system architecture, a research question could be on the usefulness of required DoDAF products. The

student could construct a survey to assess the usefulness of DoDAF products and send it out to the engineering community. An analysis of the data could justify which DoDAF products are found useful, why they are found useful, and what they are useful for. The value of such empirical data is obvious - it justifies whether or not these products should be mandated by the DoD.

Unfortunately for the average thesis writer, the time required to conduct empirical research may be longer than the time available to complete a thesis. To conduct empirical research, a thesis student needs to have a research question, prepare an instrument for data collection (e.g., a survey), obtain IRB approval of the instrument, send out the instrument, wait for responses, and then analyze the data. Much of this time is non-productive waiting time. A motivated student who identifies an interest early could possibility do the research question and instrument before getting to the last few quarters, and hence leave sufficient time to finish.

A more schedule friendly empirical study is a case study. This may be appropriate for students who worked on a program or students who have access to data. A case study is a single, but rich data point that contributes to our knowledge of systems engineering. It may be possible to do a case study, in which you the student do a task in two different ways and remark on what is learned in the process. For example, two different approaches to analyzing system reliability, and writing a detailed analysis of the pros and cons of each approach.

The empirical research approach is a great way to collect data because engineering is a human activity and the empirical research method collects the data from humans performing the engineering. While the timeline for a thesis does not support large projects, the empirical research approach can be applied in combination with other research methods. Commonly, some type of survey or interview of subject matter experts is done in a thesis to support data gather through other research means. In this way, the empirical research method can greatly enhance a thesis based largely on another research method.

### 1.3 Design Thesis

Engineers design artifacts, and an acceptable thesis research method is one in which the student designs a system or a portion of a system. Typically such a design thesis is in support of a larger, ongoing project at NPS. As an example, we have had students design a UAV launcher to support the multi-year project in swarming UAVs. The artifact under design could also be a systems engineering tool or model. For example, a student could design and develop a software program to partially populate a Test and Evaluation Management Plan (TEMP) from a set of DoDAF models. Methods and tools to partially generate many of the deliverables in a program from DoDAF products is a fruitful research area since one of the criticisms of DoDAF is its poor support of program activities. The design artifact can be hardware, software, or a process.

An important aspect of design research is building a prototype of the design. This is a necessary and important step in order to do testing and evaluation of the design. In fact, the design research method is incomplete without some sort of prototype to provide data and/or evidence of its functionality and performance. The advent of rapid prototyping capabilities for mechanical as well as electrical systems makes the design type of thesis more practical for a larger number of system types. NPS has the RoboDojo lab with 3D printing, laser cutting, and many other tools to support the rapid prototyping necessary in a design type of thesis. A design thesis describes the design problem, describes the design process, describes what was learned during the design process, and documents the success or failure of the prototypes developed and built to test the design ideas.

### 1.4 Analysis Thesis

The analysis research approach is very common in engineering theses. An analysis research method for a thesis is one in which the bulk of the thesis involves quantitative or computational analysis of a problem. For example, a research question could be, “Is it technically and operationally feasible to deploy a laser on a unmanned air vehicle?” The thesis would then try to answer the question by determining the technical

feasibility and operational feasiblility. The contribution of an analysis type of thesis is due to the depth of the analysis conducted and its ability to address the research question. The novelty of an analysis type of thesis is in the research question, the depth of analysis, and the discussion of the results. Frequently, a thesis based on the analysis approach can be greatly strengthened within an experimental framework and/or with statistical analysis of the data.

### 1.5 Combination of Research Methods

Oftentimes a thesis will use two or more of the research methods. This can be useful because each research method generates different types of evidence, which collectively can reinforce the overall thesis statement.

## 2 Thesis Characteristics

This seciton reviews thesis factors or thesis characteristics leading to success. The intent is to help the student differentiate between those characteristics that lead to a good thesis from those that lead to a poor thesis.

### 2.1 Specific and Precise Thesis Statement

A good thesis defines a narrow, specific thesis statement and then explores the topic in depth. Many students mistakenly believe the broader the scope of the thesis, then the better. These students attempt to do too much and the result is a thesis that lacks substance. In systems engineering common pitfalls include when students try to include too many systems or alternatives, they try to analyze too many aspects of the problem, or they try to do the entire sysetms engineering life-cycle. This is one of those cases where more is not necessarily better.

### 2.2 Maintain Focus on Thesis Topic

A thesis that loses focus is related to but subtly different than too broad of a topic. An unfocused thesis has a clearly defined, concise, and narrow topic, but dilutes the main message of the thesis by addressing too many ancilliary topics, which are (or should be) out of scope for the thesis. Part of thesis writing is knowing what to delete as much about what to write in the first place. A good thesis remains focused on the single claim the thesis is attempting to demonstrate with logic and other collected evidence.

### 2.3 Topic Your Advisor Has Expertise In

The thesis is an individual student-led effort, which is performed with the guidance, advice, and eventual approval of a thesis advisor. You should work in an area your advisor has some expertise in. Picking a topic in an area with which the advisor is not knowledgeable carries risk. The risk is that you work on solving a problem without knowing how it has been approached before, perhaps your solution approach is known to be faulty by experts in the area, or perhaps you are missing important information, methods, or techniques that an advisor with knowledge in the field could have directed you to. Ideally, an advisor would decline to work with a student on a thesis they were not expert in, but it is the responsbility of the student to stay within a topic their advisor has the qualifications to advise.

### 2.4 Avoiding the Conceptual Thesis

There really is no such research method called a conceptual thesis, and this is why it was not mentioned above. While all thesis should make extensive use of logical arguments to support the thesis, it is unlikely an entire thesis could be supported soley by logical argument. Moreover, a thesis that solely involves modeling or developing a conceptual framework without any data is almost always insufficient for a

thesis. Some evidence from experiments, design, empirical data, or analysis is needed to help substantiate the thesis.

### 2.5 Straying Far from Accepted Systems Engineering

Only the best students with strong convictions about their intended topic should even think about straying far from systems engineering accepted knowledge, methods, processes, and techniques. In most cases, students who stray from the larger body of knowledge end up with a poor thesis, and in some cases they are unable to complete the thesis (perhaps because nobody in the department is willing to sign off on the thesis). Remember a thesis must be substantiated with evidence derived from one of the research methods: experimental, empirical, design, or analysis. As an example, it is likely risk management models and practices are not perfect, but if your thesis idea is a complete departure from current risk management methods, then it is unlikely anybody will sign off on it unless you are able to provide substantive and compelling evidence to support it.

### 2.6 Statistical Thinking or Data Analysis

Most research methods generate data, and just having the data is insufficient. The thesis should use appropriate experimental design methods, statistical methods, and data analysis methods on the data. Experimental, empirical, and analysis types of thesis benefit from proper statistical analysis. In a design thesis, you need to actually build some prototype to test the design and data might come from the prototype. Again data analysis would be necessary.

### 2.7 Validation

In a thesis, you make a claim, you perform engineering research to gather data to prove it, and you validate your method, data, and results. A thesis that makes a claim and offers no validation of the data is a rather weak thesis. Validation is not a yes or no type of proposition, but instead should be viewed as the degree of confidence a person has in the research results. For example, if you use simulation experiments, then the validation question is how well do the simulation results match the data you expect from actual systems? The most convincing validation technique would be a statistical test such as the student t-test comparing simulation results to known actual results. However, if actual data is unavailable, there are other validation techniques such as face validity via subject matter experts, boundary testing, and so forth. The bottom line is every thesis needs some validation via data and other evidence to support the claims and evidence. All the thesis research methods have valiation. Experiments generate data for validation, empirical studies produce data for validation, design thesis create prototypes for validation, and analysis thesis generate results for validation.

### 2.8 Lack of Technical Rigor

A thesis should have a rigor at least equal to the level of the analysis done in the coursework. Actually, if the thesis topic is scoped properly, then the level of detail in the analysis should be greater than what is done in class. The reason is you have one to two quarters to do the analysis, whereas in class you probably had only one to two weeks to do something equivalent. A thesis is supposed to be a focused study so it is expected to have sufficient depth to fully explore a narrowly scoped topic.

### 2.9 Literature Review

The literature review is an important component of your research. The literature review critically assesses the scholarly peer-reviewed, archival journal articles, conference proceedings, books, and other publications in order to establish your knowledge of the research topic, identify the state-of-the-art in the field, and to put your research in context of the larger body of work. A good literature review is more than a

summary of published works. It evaluates and organizes the published research to highlight what has been accomplished and the open research questions in the field. By doing this, the literature review puts the thesis research in context of the larger body of knowledge by showing how the thesis relates to previous published works.

# 3 Conclusion

In this document, I intended to describe the nature of a systems engineering thesis. A thesis is a claim supported by data and analysis derived from one or more research methods including the experimental, design, empirical, and analysis methods. The document explained each type of research method and provided some examples. Finally, the document mentioned some characteristics of thesis that frequently lead to unsuccessful results. The purpose is to guide you away from poor approaches to thesis work.

A thesis reflects the critical thinking of the student and all the elements of critical thinking should be evident. The engineering work in a thesis should be performed with a precision and attention to details worthy of a student's best efforts. Statistical and other data analysis techniques are important since the data students gather or generate in a thesis is almost always drawn from a small sample. Lastly, the writing should be clear, concise, and direct in order to best convey the thesis contributions.

The document did not discuss many important topics including how to select a thesis advisor, how to select a topic, when to start the thesis, the NPS policies and procedures for a thesis, the issue of plagiarism, how to format the thesis, or how to write the thesis. Information and guidance on these topics are available elsewhere.

The thesis can be a challenge for many students, but it can also be highly rewarding. Theses at NPS are archived in the library and DTIC, which means that soon after publication the major search engines find and index them for worldwide consumption. Your thesis work becomes part of NPS's large contribution to systems engineering knowledge and application in military systems. Make it a good one.