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Optimization, an Important Stage of Engineering Design

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Optimization, an Important Stage of Engineering Design

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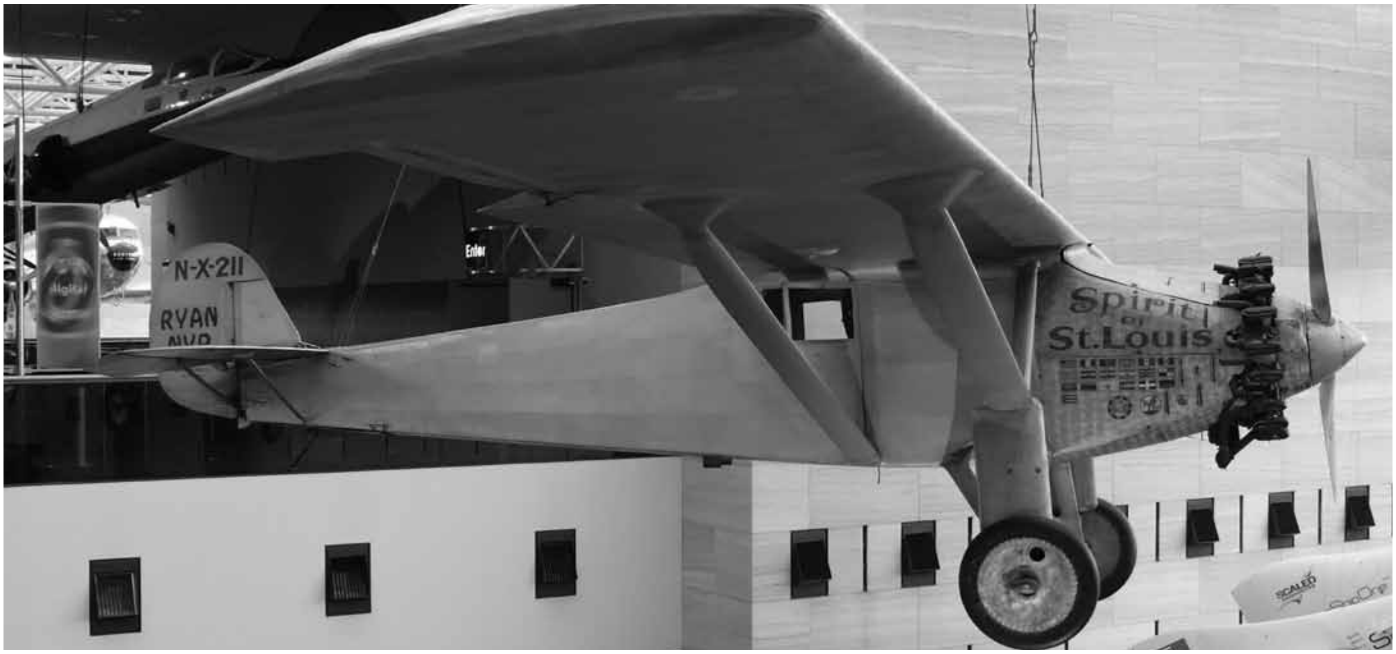
Teaching middle and high school students how to weigh constraints and criteria against various design solutions in order to select the best possible solution is an important skill necessary for engineering, as well as for life.

Charles Lindbergh's *Spirit of St. Louis:* An Example in Optimization.

Introduction

A number of leaders in technology education have indicated that a major difference between the technological design process and the engineering design process is analysis and optimization (Hailey, et al., 2005; Hill, 2006; Gattie & Wicklein, 2007). The analysis stage of the engineering design process is when mathematical models and scientific principles are employed to help the designer predict design results. The *optimization* stage of the engineering design process is a systematic process using design constraints and criteria to allow the designer to locate the optimal solution. In an engineering design approach, both analysis and optimization are employed before any prototype work is started.

Recently, the author conducted research to examine the status of technology education regarding the infusion of engineering design concepts (Kelley, 2008). Participants from this study revealed that technology education curriculum content currently does not emphasize optimization techniques as a part of the engineering design process. One of lowest-ranking survey items for time per typical use was the item: *use optimization techniques to determine optimum solutions to problems,* mean of 1.82 using a 5-point Likert scale. In the author's search to understand why technology educators have not emphasized this phase of the engineering design process to a greater degree, the author discovered that there was very little in engineering design textbooks or engineering design curriculum at the secondary level regarding optimization. One of the few pre-engineering sources that broached the subject, *Engineering Your Future,* (Gomez, Oakes, & Leone, 2006) dedicated only one page to optimization. However, the members of the National Center for Engineering



Spirit of St. Louis photographed at National Air and Space Museum.

and Technology Education (NCETE) have identified optimization as an important concept in engineering design (Merrill, Custer, Daugherty, Westrick, & Zeng, 2007).

NCETE members have identified three specific core design concepts important in the engineering design process and have termed these concepts *Constraints, Optimization,* and *Predictive Analysis* or COPA. The COPA concept has been used to help technology education teachers quickly identify the core concepts of engineering design. NCETE has developed some activities designed to deliver COPA in technology education. This article will focus specifically on *Optimization* as a way to inform technology educators about the concept and provide an example of optimization through the case of Charles Lindbergh's famous 1929 flight from New York to Paris. The author will present a historical case using Lindbergh's own words from his biography, *The Spirit of St. Louis* (1953), to illustrate that he used an optimization process to make design decisions about his plane and flight, which led to his success much more than just being "Lucky Lindy."

Optimization Defined

One of the simplest definitions for optimization is "doing the most with the least" (Gomez, et al. p. 301, 2006). Lockhart and Johnson (1996) define optimization as "the process of finding the most effective or favorable value or condition" (p. 610). The purpose of optimization is to achieve the "best" design relative to a set of prioritized criteria or constraints. These include maximizing factors such as productivity, strength, reliability, longevity, efficiency, and utilization. (Merrill, Custer, Daugherty, Westrick, & Zeng, 2007). Engineers are often assigned design projects that require them to seek a solution that efficiently locates a design that meets the identified criteria within the given constraints. Koen (2003) defines the engineering method as "the strategy for causing the best change in a poorly understood situation within the available resources" (p. 7). Engineers are often forced to identify a few appropriate design solutions and then decide which one best meets the need of the client. This decision-making process is known as optimization.

Lindbergh and *The Spirit of St Louis:* An Example in Optimization

When Lindbergh set out to win the Orteg prize for being the first aviator to fly nonstop from New York to Paris, the aviation technology was available to accomplish such a goal. However, other aviators more experienced than Lindbergh (Byrd, Davis and Wooster, Fokker, and Nungesser) attempted the nonstop flight, resulting in crashes at takeoff or losses at sea (Lindbergh, 1953). These failures did not occur because the famous flyers lacked

The Spirit of St. Louis: close-up of the right side of the fuselage.

the advanced technology of the time or because they were unskilled fliers. Money was not an issue: aviators such as Byrd, Fonck, Davis, and Nungesser poured thousands of dollars into multiple-engine airplanes, some of which never lifted off the ground. Why was Lindbergh successful? He optimized for the best available solution *(The Spirit of St Louis)* under the given constraints and conditions—a technique Lindbergh learned as an engineering student at the University of Wisconsin. There were many issues for Charles Lindbergh to consider as he planned for his nonstop transcontinental flight. At the forefront of all of his concerns was, of course, his safety. Lindbergh (1953) writes:

> "Safety at the start of my flight means holding down weight for the takeoff. Safety during my flight requires plenty of emergency equipment. Safety at the end of my flight demands ample reserve of fuel. It is impossible to increase safety at one point without detracting from it at another. I must weigh all these elements in my mind, and attempt to strike some balance" (p.97).

What Lindbergh illustrates through these words is that to *engineer* anything requires decision making and balancing constraints and criteria to implement the best possible solution. Let's review the final decisions that Lindbergh made for the design of his aircraft and the plans of his flight assessed against the constraints and criteria he listed above: (1) keeping weight down, (2) safety during flight, and (3) ample reserve of fuel.

The first constraint, *keeping weight of the plane down,* directly correlates to the design criteria *ample reserve of fuel.* In order to keep weight down, Lindbergh's first design choice was something the other aviators never considered, a single-engine monoplane. When challenged by financial backers to consider a multiengine plane, Lindbergh responded, "I'm not sure three engines would really add much to safety on a flight like that (over water). There'd be three times the chance of engine failure; and if one of them stopped over the ocean, you probably couldn't get back to land with the other two. A multiengined plane is awfully big and heavy" (Lindbergh, 1953, p.26). Lindbergh also chose a monoplane over a biplane. When asked about this decision, Lindbergh said, "it [monoplane] is more efficient than a biplane, there's more room in the wing for gasoline, and it can carry more ice (on the wing)" (p. 103).

Another decision made by Lindbergh to keep the weight down was to fly the plane solo. Clearly the greatest risk in Lindbergh's plan was flying solo for over 33 hours and 30 minutes. However, Lindbergh believed flying alone was his greatest asset. "By flying alone, I've gained in range, in time, in flexibility; and above all, I've gained in freedom" (p. 192). By flying alone, Lindbergh was able to add more weight in the form of additional fuel necessary to make the transatlantic flight and ensure that he had a safety cushion of extra fuel in case of a navigational error or if forced to turn back due to inclement weather. This decision addressed all the major constraints and criteria: (1) keeping weight down, (2) safety during flight, and (3) ample reserve of fuel.

Lindbergh made some decisions about what to carry and, more specifically, what not to carry, that might cause some to wonder if he had carefully considered his own safety during flight. For example, Lindbergh chose not to carry an aircraft radio, a parachute, or a sextant (tool for navigation). These items seem necessary for a pilot's safety. However, through the optimization process, Lindbergh rationalized that these items would cost more in added weight to the plane than they would be worth in practical usage. The parachute was a tough item to reject; however, Lindbergh provides a logical rationale for not carrying one. "I considered carrying a parachute, but decided against it. A parachute would have cost twenty pounds—a third of an hour of fuel—enough food and water for many days" (pp. 212-213). Lindbergh also supported his decision to not carry a parachute with the rationale that he could only use a parachute in one part of the journey (over Nova Scotia). Lindbergh's flight pattern had him flying too low for a parachute (over Long Island and New England), over water, or (over Europe) when the plane would be light enough for a safe stall-landing.

Lindbergh chose not to carry a naval radio because, at the time, these instruments were very heavy, difficult to use, and were unreliable. Lindbergh wrote: "I find that naval radios are much too heavy for my single-engine plane, and that their value on a flight like mine is doubtful" (p. 96).

He addresses the issue of not carrying a sextant when he wrote: "I couldn't possibly use a sextant . . . I couldn't take a sight and fly the plane at the same time. The slightest turn throws the bubble off. *The Spirit of St Louis* won't hold a straight course for two seconds by itself. Besides, there's the weight—you can't carry everything on a record flight" (p.237). "If we'd tried to carry every safeguard, the plane couldn't have gotten off the ground—dump valves, parachute, radio, sextant" (p.237). In fact, that is certainly one reason why Byrd, Fonck, Davis, and Nungesser crashed on takeoff; they all tried to carry more weight than the plane could handle. Lindbergh rationalized these decisions by determining what he gained by giving up these items. He wrote: "We'll trade radio and sextant weight for extra gasoline. What I lose in navigational accuracy, I hope to gain twice over in total range" (p. 96).

Lindbergh did choose to carry some items for personal safety, including a rubber boat, red flares, emergency food rations, and an extra gallon of drinking water. In all, these items weighed over 30 lbs; equivalent to over a half an hour of flying time in fuel weight. These items, Lindbergh considered, were optimal options for the conditions he would be under during his flight.

Lindbergh had aeronautical engineers working with him, as Ryan Air custom designed and built *The Spirit of St. Louis.* Lindbergh made final decisions on how the plane was designed. One unique feature of the aircraft was the location of the cockpit behind the gas tank. Lindbergh believed that locating the cockpit behind the gas tank gave him a better chance in case of a crash landing. This was a very abnormal design that placed the gas tank in the view of the pilot. That fact was no issue to Lindbergh; he decided to design the plane without a windshield. He writes: "There is not much need to see ahead in normal flight. I won't be following any airways . . . All I need is a window on each side to see out through. The top of the fuselage could be the top of the cockpit. A cockpit like that wouldn't add any resistance at all" (p.87). Remember, Lindbergh, like all good engineers, made decisions based upon defined criteria and identified constraints. In this case, Lindbergh, in his own words writes, "I think we ought to give first consideration to efficiency in flight; second to protection in a crack-up; third, to pilot comfort (p. 99). Lindbergh also had to consider keeping costs down, so he chose to keep the design of the plane very simple with no fancy extras, and as a result, his budget was under $15,000 compared to others such as Davis, who spent $100,000 on his plane.

Optimization in the Classroom

There are many teaching strategies that can be employed to include the optimization process in a technology education program. Certainly, any technology education program that includes engineering design projects should include an optimization phase of the design process. This can be accomplished by requiring students to keep records of their design thinking and decision making in an engineer's notebook. The technology education teacher could require that students list possible solutions and provide rationale for why they selected their final design solution, which would require students to carefully think through the various options and how each option impacts the design solution. Thinking optimally is a skill that must be developed.

Technology education teachers could help students develop these skills by conducting an in-class discussion about a technological problem as a way to work through the optimization process. For example, an in-class discussion about the rising cost of gasoline could be an interesting technological problem to explore through the optimization process. Students could brainstorm possible solutions, and as a class they could seek to locate multiple solutions that meet class-defined constraints and criteria, and discuss the potential benefits and pitfalls until the class locates the optimal solution. If the class explored all of the positive and negative impacts fossil fuel-based technologies have on society, the economy, politics, and the environment, then the exercise would address Standards 4, 5, and 6 of *Standards for Technological Literacy: Content for the Study of Technology.* (ITEA 2000/2002/2007). Classroom exercises like the one described here can be very beneficial for students to learn how to systematically make decisions based upon identified constraints and defined design criteria. Decision making is a very important skill for life and, let's face it, middle and high school students often lack the ability to make important informed decisions.

Closing

Proponents of engineering design have challenged technology educators to move away from the trial-and-error approach of testing design solutions in favor of employing *analysis* (using mathematical models and science concepts to predict design results) and *optimization* (systematic process using design constraints and criteria to locate the optimal design) (Hailey, et al., 2005; Hill, 2006; Gattie & Wicklein, 2007).

Classical Engineering Design Process (From introductory engineering text by Eide, et al.)	**Grades 9-12 *STL* Design Process** (from *Standards for Technological Literacy)*
1. Identify the need	1. Defining a problem
2. Define problem	2. Brainstorming
3. Search for information	3. Researching and generating ideas
4. Identify constraints	4. Identifying criteria and specifying constraints
5. Specify evaluation criteria	5. Exploring possibilities
6. Generate alternative solutions	**6. Select an approach and develop a design proposal**
7. Engineering Analysis	**7. Building a model or prototype**
8. Optimization	**8. Testing & evaluating the design using specifications**
9. Decision	**9. Refining the design**
10. Design Specification	**10. Creating or making it**
11. Communication	11. Communicating process and results

Table 1. Comparison of an Introductory Engineering Design Process with the *STL* Standard 8 Design process

Charles Lindbergh and the design of *The Spirit of St. Louis* provides an example of how an engineer weighs constraints and design criteria to locate the optimum solution. The author hopes that, through this example, technology education teachers will be inspired to use pedagogical approaches that implement optimization techniques. Several suggested approaches to optimization for technology education include using an engineer's design notebook to record design thinking and decision making, and leading class discussions on the impact of technology, allowing students to optimize the best solution with the fewest negative impacts. Another optimization technique is using a decision matrix that allows students to assign weights to constraints and criteria as a way to systematically locate the optimum design solution. (See http://deseng.ryerson.ca/xiki/Learning/Main:Decision_matrix for details about creating a decision matrix.). In order for technology education to move toward an engineering design focus, it is critical to employ these optimization techniques that are recognized as authentic engineering design strategies.

The efforts taken here to explain the term optimization have been made using simple design terminology—not to trivialize the optimization process but to provide a simple example. In the engineering discipline, optimization can involve many complicated mathematical formulas necessary for locating optimal solutions to complex engineering problems. However, teaching middle and high school students how to weigh constraints and criteria against various design solutions in order to select the best possible solution is an important skill necessary for engineering as well as for life.

Table 1 provides a side-by-side comparison of an engineering design process and the technological literacy design process, revealing major differences in the two approaches to design, highlighted here in bold. The engineering analysis and optimization stages of the engineering design process provide the designer with decision-making "tools" for making informed decisions about design solutions before a final design is selected and a prototype is built.

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Resource

www.charleslindbergh.com/hall/spirit.pdf

The technical report for the Lindbergh flight, created by Ryan Air. It shows all the calculations that were done to locate optimal air speed, gas mixture ration, etc. Teachers could use the airplane design as an engineering case for their class to study.

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