Strategic Technology Maturation and Insertion (STMI): a requirements guided, technology development optimization process

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James Brill Clegern
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Abstract

This research presents a Decision Support System (DSS) process solution to a problem faced by Program Managers (PMs) early in a system lifecycle, when potential technologies are evaluated for placement within a system design. The proposed process for evaluation and selection of technologies incorporates computer based Operational Research techniques which automate and optimize key portions of the decision process. This computerized process allows the PM to rapidly form the basis of a Strategic Technology Plan (STP) designed to manage, mature and insert the technologies into the system design baseline and identify potential follow-on incremental system improvements. This process is designated Strategic Technology Maturation and Insertion (STMI).

Traditionally, to build this STP, the PM must juggle system performance, schedule, and cost issues and strike a balance of new and old technologies that can be fielded to meet the requirements of the customer. To complicate this juggling skill, the PM is typically confronted with a short time frame to evaluate hundreds of potential technology solutions with thousands of potential interacting combinations within the system design. Picking the best combination of new and established technologies, plus selecting the critical technologies needing maturation investment is a significant challenge. These early lifecycle decisions drive the entire system design, cost and schedule well into production

The STMI process explores a formalized and repeatable DSS to allow PMs to systematically tackle the problems with technology evaluation, selection and maturation. It gives PMs a tool to compare and evaluate the entire design space of candidate technology performance, incorporate lifecycle costs as an optimizer for a best value system design, and generate input for a strategic plan to mature critical technologies. Four enabling concepts are described and brought together to form the basis of STMI: Requirements Engineering (RE), Value Engineering (VE), system optimization and Strategic Technology Planning (STP). STMI is then executed in three distinct stages: Pre-process preparation, process operation and optimization, and post-process analysis. A demonstration case study prepares and implements the proposed STMI

process in a multi-system (macro) concept down select and a specific (micro) single system design that ties into the macro design level decision.

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1 Introduction

This research explores a formalized and repeatable Decision Support System (DSS) process to allow Program Managers (PMs) to systematically tackle the problems (time, bias, interactions, risk, and resources) with technology evaluation and inclusion into a system design. The proposed process incorporates computer based Operational Research techniques which automate and optimize key portions of the decision process. This computerized process provides the PM a DSS tool to rapidly compare and evaluate candidate technology performance, incorporate lifecycle costs for inclusion into a best value system design, and generate input for a Strategic Technology Plan (STP) to mature enabling technologies. This process is designated Strategic Technology Maturation and Insertion (STMI).

Traditionally, to build this STP, the PM must juggle system performance, schedule, and cost issues and strike a balance of new and old technologies that can be fielded to meet the requirements of the customer. To complicate this juggling skill, the PM is typically confronted with a short time frame to evaluate hundreds of potential technology solutions with thousands of potential combinations within the system design. The PM's STP generation must balance the cost and schedule to mature new technologies against the selection of existing technologies to meet the customer requirements of the system design.

1.1 <u>Background</u>

In industry and the Department of Defense (DoD), strategic technology planning is used for critical business growth and procurement of technology intensive equipment. Generating a STP involves satisfying a multitude of stakeholders, meeting internal and external requirements, maturing the technology and finally inserting the technology into a usable system or product. An effective STP directs the focus of industry's competitive edge, and allows entities like DoD to project requirements and focus development to meet evolving user requirements[1,2,3]. Typically, for both industry and the DoD, a PM is designated to develop a STP for each system acquisition program. The PM provides direction to the development, production, evaluation and initial deployment of a new technology system. The PM's goals are to meet the customer requirements efficiently and effectively in the shortest time possible. In order to perform those duties, the PM must have an effective technology planning and investment program early in the system's lifecycle and be able to track the technology development progress.

The early STPs traditionally require large teams of Subject Matter Experts (SMEs), informal evaluations and "rules of thumb" heuristics to narrow the technology choice options to a manageable subset for detailed evaluation. There are typically five problem areas with the traditional technology evaluation process: time, bias, interactions, risk, and resources. The first problem is that the technology analysis is usually time limited, shortchanging the examination of all the presented alternatives. The second problem incorporates human biases discarding large swaths of potential solutions in favor of known capabilities and development timelines. The third problem is that interactions between technologies are often difficult for SMEs to manually evaluate except through modeling or experimentation. The fourth problem is the American love affair with things new and high tech, and our tendency to accept these higher risk (immature), but "glamorous" technology options and not account for lifecycle cost impacts. The fifth problem is the tendency to ignore the significant amount of resources and time needed to mature a technology for effective insertion into a system design. These five problem areas limit analysis, resulting in potentially poor management decisions. These poor decisions then drive the entire system design, cost and schedule well into production.

While problem areas one through four must be addressed in a technology evaluation for a system design, the fifth problem area also involves an additional requirement. This requirement is for a formalized process identifying which technologies need to be matured and transitions from a lower Technology Readiness Level (usually a TRL-4 or 5) to a TRL-6 prototype for insertion into an integrated system design as outlined in the GAO report NSIAD-99-162[4]. The DoD technology development community and laboratories often refer to this TRL transition effort as the "Technology Chasm"[5,6,7] owing to the high frequency of great new technologies being shelved due to a lack of development funding. Other researchers have investigated technology transfer processes to facilitate technology maturation, primarily offering manual processes and models[8,9,10] but, making errors in bridging this “technology chasm” have far reaching impacts to the system in design.

Impacts of unrealistic or unplanned technology maturation within a system design will typically follow this path:

1. Unplanned technology maturation raises projected costs over initial estimates and stretches the planned schedule
2. Late delivery of technology maturation cause design changes to ripple through the program late in the program cycle
3. Failed or undeliverable technologies are replaced by fallback technologies causing expensive additional design and production changes
4. Fallback technologies often fail to meet customer requirements
5. Customers will often cancel the program when their needs are not met

The PM’s primary goal is the successful design, production and delivery of a system to his customer at an acceptable cost. In order to accomplish this he needs to minimize the risk to the system under development. Tools that reduce this risk through repeatable, analytical processes that can be subjected to rapid trade studies, sensitivity analysis and optimized for certain user preferred variables (schedule, cost, or performance parameters) are highly desired.

1.2 Research topics

To help the PM minimize the impacts of spanning the “Technology Chasm” with poor technology maturation planning, an efficient decision support tool is needed. This tool or system must provide a rigorous and repeatable process to examine technology options early in the system design and present an optimized STP path. Some of the common technology planning issues being addressed by PMs make excellent questions addressed by this research.

- Can all candidate technologies be evaluated against a common set of customer requirements, not just trendy or directed technology options?

- Can interactions between technology options be addressed in an initial system design?
- Can a budget and schedule of optimized current and developing technologies be generated to help a PM generate a Strategic Technology Plan for technology investment?
- Can a Value Engineering “best value” system design be incorporated with the proposed system lifecycle design?
- Can trade studies be conducted to illustrate how technology selection and maturation is impacted by changing customer requirements?
- Can sensitivity analyses be conducted to illustrate how technology selection and maturation is impacted by data uncertainty in the estimates of technology performance, cost and schedule?
- Can a technology maturation process provide feedback to inform customers concerning obtainable and unobtainable requirements given current technology levels, funding and schedules?

To answer these research questions, a formalized and repeatable Decision Support System (DSS) process to allow PMs to systematically compare and evaluate candidate technologies against a common set of requirements is explored in this research. This developed DSS process generates data for a recommended STP that identifies immature technologies needed for a system design and helps the PM to plan to bridge the TRL-4 to TRL-6 technology “chasm” with direct applications to technology maturation, transfer and insertion into product systems designs.

1.3 <u>Research objectives</u>

STPs have been an active field of research in many areas within the DoD acquisition “lifecycle” timeline. Researchers, developers and program managers have expended enormous time and resources to study and develop methodologies to improve how technology is identified, matured and eventually inserted into a viable product or service. Despite a growing body of literature and government regulations, STP is primarily a subjective methodology conducted by SMEs. Applying a systematic analysis process offers a potential DSS method to make planning and technology forecasting more accurate and defendable given the inter-connected nature of customer requirements and technology interactions.

There are three STMI operational areas or stages developed in this research and illustrated in Figure 1: Pre-process preparation, process operation and optimization, and post-process analysis. The focus of the research will be to demonstrate the proposed process and applicability as a planning tool for the PM. The goal of the STMI process is to provide decision makers with an additional DSS tool to systematically and rapidly evaluate multiple technology options and recommend an optimized technology set for STP generation that will complete a system design ready for TRL-6 prototyping.

Stage one involves the pre-process preparation of customer requirements, operational scenario and technology data. These are inputs to the second STMI process stage and are critical due to the fact that if the requirements are not solid, if the operational scenario models are not representative and if the technology data is not accurate, the results are the traditional GiGO (Garbage In, Garbage Out). This stage confirms a reference Coordinated Requirements Document (CRD) that details measurable, testable and accepted requirements/constraints agreed to by the customer and PM team. After CRD generation and based on the operation scenario, impartial Subject Matter Experts (SMEs) generate system design models and a technology database that identifies potential technology options, documents performance parameters and estimates maturation/lifecycle costs and schedules. This technology database “Metadata” is referenced back to the CRD and follows the technologies as they are evaluated further in the STMI process.

The research objectives of the STMI stage one include:

1. Review and summarize the related research in literature
2. Provide recommendations for generating a system operational concept and reference CRD
3. Provide recommendations for generating the system design models
4. Provide recommendations for generating the technology database
5. Implement the recommendations in the research case study

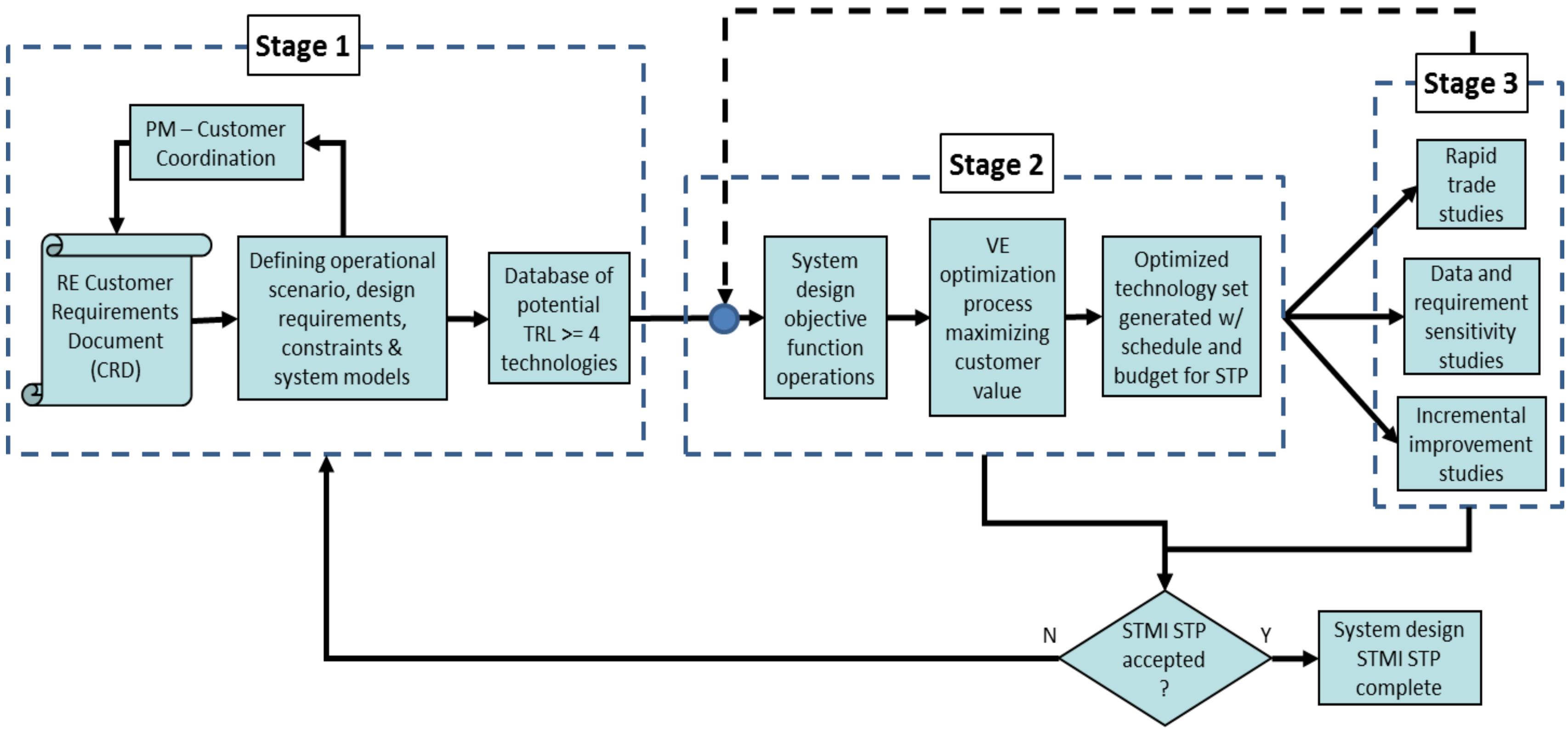

Figure 1: Three stages of the proposed STMI process

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Once the pre-process preparation of stage one has been completed, STMI stage two engages the principles of Value Engineering (VE) to generate a Best Value system design optimization with the requirements, constraints, models and technology database provided in stage one. Objective functions are generated from the stage one information and system design model recommendations and are used to evaluate the technology sets making up potential system designs. The STMI VE process assesses the value of each successful system design and ranks the designs with the optimum having the best score or "best value". The outputs of the "best value" solution process allow the PM the flexibility to rapidly evaluate and generate data for a STP which has addressed five of the typical technology evaluation problems:

1. Time: Analysis is computer based, greatly decreasing "by hand" analysis calculations and allowing rapid analysis of requirements change or new technology data
2. Bias: Eliminates bias by evaluating all candidate technologies against the same customer requirements, not just trendy or directed technical options
3. Interactions: Accounts for secondary interactions between technologies that impact multiple areas of a system design through the object function
4. Risk: Identifies critical technology areas that require primary development funding and schedule to reduce risk
5. Resources: Account for lifecycle resources and cost impacts of each technology option

The research objectives of the second STMI stage include:

1. Review and summarize the related research in literature
2. Develop a process for STMI to evaluate potential system designs and account for technology interactions
3. Design and implement a system design optimizer based on VE "best value" criteria
4. Select the optimized "best value" system design and create data inputs for a STP which advances required technologies, including developing TRL-4 through TRL-6 technologies, for system integration

5. Adapt process for a spreadsheet “all option” case study analysis
6. Identify a potential metaheuristic process to reduce system design computational requirements for follow-on research to implement

The STMI stage three process is the ability to rapidly conduct trade studies, sensitivity analysis and incremental improvement analysis. Requirement trade studies are commonly used in the design of aerospace vehicles and software selection[11] to aide customers in fine-tuning requirements and their cascading impacts to system designs. Sensitivity analysis studies would examine the impacts of data uncertainty on the end optimization results[12]. Incremental improvement studies would examine significant changes in customer requirement thresholds to justify a new system design delivery or “increment,” and generate a new STP which could be executed in parallel with the original design STP[13].

The research objectives of the third STMI stage include:

1. Review and summarize the related research in literature
2. Provide recommendations and examples for conducting trade studies with STMI
3. Provide recommendations and examples for conducting single and multiple variable sensitivity studies with STMI
4. Provide recommendations for conducting future incremental designs
5. Demonstrate recommendations in a case study analysis

This research also provides a case study implementing the proposed process. Since traditional linear programming is not well suited to this type of multi-factor, non-linear optimization, an “all-case” analysis model of this process was used to maximize the “best value” of the solution with the demonstration technology database. The model was developed in the context of a multi-dimensional knapsack problem, and seeks to maximize the best value of the solution while meeting the customer threshold requirements.

1.4 Structure of the dissertation

The rest of this dissertation research is organized as follows. Chapter two reviews the existing literature on current DSS development and four enabling concepts that are brought together to form the basis of STMI: Requirements Engineering (RE), Value Engineering (VE), system optimization, and Strategic Technology Planning (STP). Chapter three develops the STMI process model for the technology maturation problem and STP generation. Chapter four presents the proposed research method through a case study and examines optimization speed and data sensitivity within the STMI process. Chapter five provides conclusions and expected contributions. Chapter six outlines future research opportunities.

2 Literature review

2.1 Decision Support System

Since the early 1970's and the advent of computer based systems aiding decision making, Decision Support System (DSS) has evolved as computer capabilities have grown[14]. DSS is a general term for any computer application that enhances a person or group's ability to make decisions. In order to survey DSS development and applicability, a background review is presented first. Then a historical development, components and applications of DSS are examined. Finally, STMI as a DSS technique is proposed.

2.1.1 DSS background

Decision making is an essential part of management planning[15]. To assist a PM analyzing potential technology options for a system design and STP, a DSS can be employed to help make decisions in this fluid and rapidly changing technology environment. A typical DSS is interactive and provides the PM with easy access to decision models and data to support decision-making tasks. It utilizes a computer-based information system that supports management, operations, and planning levels of an organization (usually mid and higher management). A DSS can be either fully computerized, human or a combination of both and are typically characterized by[16]:

1. DSS tends to be aimed at the less well structured, underspecified problem that upper level managers typically face
2. DSS attempts to combine the use of models or analytic techniques with traditional data access and retrieval functions
3. DSS specifically focuses on features which make them easy to use by non-computer people in an interactive mode
4. DSS emphasizes flexibility and adaptability to accommodate changes in the technology environment and the decision making approach of the user

DSSs often include knowledge-based systems with an interactive software-based system intended to help decision makers compile useful information from a combination of raw data, documents, and personal knowledge, or business models to identify and solve problems and make decisions.

Since the PM is not likely to have a detailed knowledge of the technology's options, models or their ability to meet customer requirements, a DSS can help reduce the time required to conduct this level of analyses. It improves the PM's effectiveness in making decision where a manager's judgment is still essential[17].

2.1.2 DSS historical development

From the early days, it was recognized that DSS was an applied discipline that used knowledge and theory from many supporting disciplines. For this reason, many DSS research questions have been examined because they were of concern to the people using the specific DSS supporting operations decision making, financial management or strategic decision-making[18]. The concept of decision making support evolved early in the era of distributed computing and incorporated two main areas of research: The theoretical studies of organizational decision making done at the Carnegie Institute of Technology during the late 1950s and early 1960s, and the technical work on interactive computer systems through Project MAC[19] from the Massachusetts Institute of Technology in the 1960s[20]. DSS became an area of research of its own in the middle of the 1970s when business journals began to publish articles on management decision systems[21] and a dedicated technical journal was devoted to exploring DSS applications[22].

The definition and scope of DSS has evolved over the years. In the 1970s DSS was described as "a computer-based system to aid decision making". In the late 1970s the DSS movement started focusing on "interactive computer-based systems which help decision-makers utilize data bases and models to solve ill-structured problems". In the 1980s DSS provided systems "using suitable and available technology to improve effectiveness of managerial and professional activities" within financial planning systems, spreadsheet-based analysis and data warehouses[23]. In the middle and late 1980s, executive information systems (EIS), group decision support systems (GDSS), and organizational decision support systems (ODSS) evolved from the single user and model-oriented DSS[24]. As the turn of the millennium approached, On-line Analytical Processing (OLAP), business intelligence and new Web-based analytical applications were introduced. The advent of better and better computing and reporting technologies has seen DSS start to emerge as a critical component of management system design.

In recent years, the Web has had the most significant impact on the variety, distribution and sophistication of DSS, but handheld PCs, wireless networks, expanding parallel processing coupled with very large data bases and visualization tools are continuing to encourage the development of innovative decision support applications. Future DSS will use faster, real-time access to larger, better integrated databases. Models within the newer DSS will be more complex, interactive and progressively more user friendly. Systems built using simulations and their accompanying visual displays will be increasingly realistic[25].

2.1.3 DSS categories

In 1980, Steven Alter published his MIT doctoral dissertation results in an influential book. His case studies provided a firm descriptive foundation of decision support system examples. Alter concluded that decision support systems could be categorized in terms of the generic operations that can be performed by such systems. These generic operations extend along a single dimension, ranging from extremely data-oriented to extremely model-oriented. Alter conducted a field study of 56 DSS that he categorized into seven distinct types of DSS[26]. His seven types include:

1. File drawer systems that provide access to data items.
2. Data analysis systems that support the manipulation of data by computerized tools tailored to a specific task and setting or by more general tools and operators.
3. Analysis information systems that provide access to a series of decision-oriented databases and small models.
4. Accounting and financial models that calculate the consequences of possible actions.
5. Representational models that estimate the consequences of actions on the basis of simulation models.
6. Optimization models that provide guidelines for action by generating an optimal solution consistent with a series of constraints.

7. Suggestion models that perform the logical processing leading to a specific suggested decision for a fairly structured or well-understood task

Taking a look at the internal working of a DSS, Dr. Kailash Joshi, from the University of Missouri-St. Louis[27], indicates that each DSS contains three principal subsystems with the following capabilities:

1. Data management subsystem of a DSS supplies data to which the models can be applied. It relies, in general, on a variety of internal and external databases. The power of DSSs derives from their ability to provide easy access to data. The database administrator needs to pay particular attention to data consistency and accuracy.
2. Model Management Subsystem maintains the libraries of models. A particular advantage of DSS is the decision maker's ability to use a model to explore the influence of various factors on outcomes (trade studies).
3. User Interface Subsystem supports the user in applying models to data. The notable feature is support of multiple forms of input and output.

DSS incorporate a wide variety of disciplines and input actors contributing to the DSS design and operation. The basic construction and operations format of a DSS is illustrated in Figure 2.

2.1.4 STMI as a DSS process

The initial proposed STMI DSS process identifies as an “optimizing” DSS and incorporates all three of the primary DSS components in a proof-of-concept spreadsheet model. But, a spreadsheet DSS model is limited in the data-handling capabilities (cannot work with large databases), limited in model complexity, and modifications to spreadsheets are difficult to keep updated[28]. Future STMI developments will require evolving past the initial proof-of-concept spreadsheet into a dynamic programing environment with a graphical user interface to facilitate user interaction.

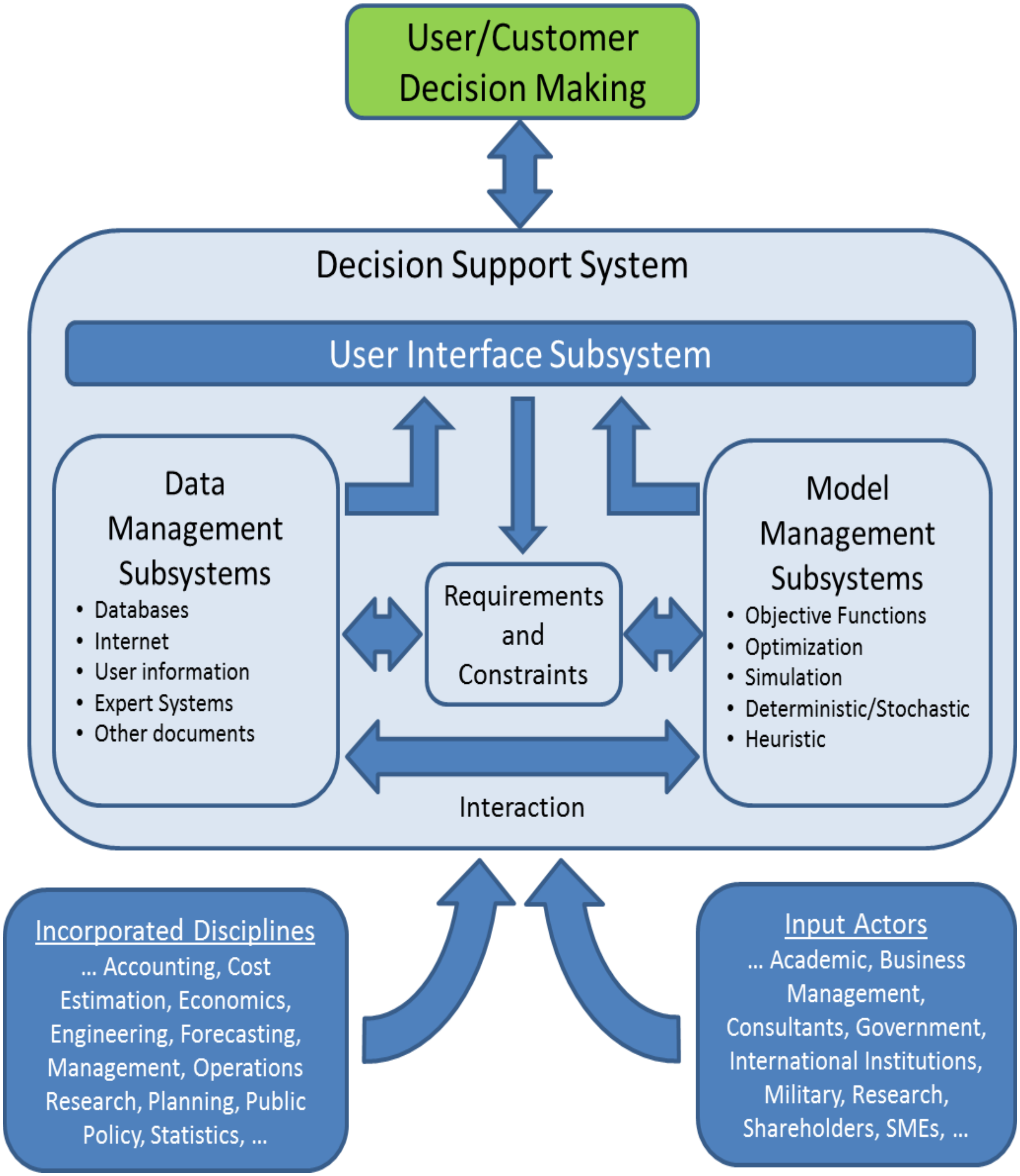


Figure 2: DSS operation overview

2.2 Requirements Engineering

Engineering systems are designed, and anything that is designed has an intended purpose. If a system design is unsatisfactory for the customer, it is because the system was designed without an adequate understanding of its purpose. This problem can be mitigated by careful analysis of purpose throughout a system's life. Requirements Engineering (RE) provides a framework for understanding the purpose of a system and the operational environment in which it will be used. Or put another way, RE bridges the gap between an initial vague recognition that there is some problem to which we can apply technology, and the completing the task of building the best system to address the problem.

2.2.1 RE background

RE is the general discipline that governs customer requirements generation prior to entering system design, where "customers" are defined as organizations or stakeholders responsible for the primary functions of a system design[29]. RE was accepted as being coined in a 1979 TRW technical report[30] and generally includes the following seven steps[31]:

1. Requirements inception: identification of a system objective. "What does the customer want the system to be able to do?" Without a solid vision of what the system needs to do, the rest of RE becomes unsustainable. This step yields a statement or operational concept detailing the system objectives.
2. Requirements identification: identifying existing and new requirements or constraints that meet the system objective. These must be quantifiable, measurable and testable. This is also known as the requirements gathering or requirements elicitation stage. The primary types of requirements include: Customer (What do they want?), Functional (What should it do?), Performance (How well should it do it?), Interfaces (What should it work with?), Environment (Where should it be able to work?) and Design (What code, regulation or specification must be met?). Typical requirement inputs include needs and objectives, organization missions, lifecycle sustainability concepts, operating

environments, technology base, laws/policies, and organizational controls/limitations.

3. Requirements analysis and negotiation: checking requirements and resolving customer conflicts. This is the requirement engineer's clarification stage with the customer and time for pruning a mass of requirements and constraints to a manageable set. Requirements analysis results in a clear understanding of system functions, expected performance, interfaces, environmental and design constraints.
4. Requirements specification: documenting the requirements in a Customer Requirements Document (CRD) and identifying their references. In the testing community, this is referred to as the Test Requirements Document (TRD). All technology offered for examination in a system must be able to be tied back to the CRD to meet a requirements reference point.
5. System modeling: developing the models and technology databases of the proposed system. These are the mathematical models that become the objective function, the constraints used to limit the system design, and the database of technology used in the modeling to meet the customer requirements. Functional modeling is a common method to integrate Inputs (requirements), Controls (constraints & system concept choices), Enablers (SME databases) and Outputs (results)[32].
6. Requirements validation: checking that the documented requirements and models are consistent and meet stakeholder needs. Can the proposed system model actually design something the customer wants that is within the relevant range of the technology specifications?
7. Requirements management: managing changes to the requirements as the system is developed and put into use. This is also known as configuration control to document when a change is requested, why it is needed and any impact to the design that occurs from the changes.

RE is not a single event, but a component of the system lifecycle that tries to keep all the players on the same development path by identifying, agreeing on, documenting, validating and managing the aspects of customer requirements. This feeds into common wisdom of, ‘A system is only as good as the requirements from which it is developed.’

2.2.2 RE strategies

While known as the general discipline of “Requirements Engineering”, RE has been documented in many text books noted in Table 1. RE even has its own technical journal devoted to exploring RE applications[33]. RE strategy methods offer users systematic ways to deal with complex systems, mainly by breaking down complex problems into simpler ones that can be understood better.

Table 1: A selection of current academic RE textbook references

Author(s)	Title	Publisher	Year
Hull, E., Jackson, K., and J. Dick	Requirements Engineering	Springer	2010
Robertson, S., J. Robertson	Mastering the Requirements Process: Getting Requirements Right	Pearson Education	2012
Pohl, K..	Requirements Engineering: Fundamentals, Principles, and Techniques	Springer	2010
Stevens, R., Brook, P., Jackson, K. and Arnold S.	Systems Engineering: Coping with complexity: Chapters 2 & 3.	Prentice Hall Europe	1998
Sutcliffe, A.G.	The Encyclopedia of Human-Computer interactions (Chapter 13: Requirements Engineering)	Interaction Design Foundation eBooks[35]	2013
Van Lamsweerde, A.	Requirements engineering: From system goals to UML models to software specifications	Chichester: Wiley	2009
Wieringa, R.J.	Requirements Engineering: Frameworks for understanding	Wiley	1996

RE strategies can be placed into three broad categories: “Waterfall” or sequential, “spiral” or Iterative, and “staged” or incremental. In each of the categories of RE, the seven steps are completed in various levels of detail, sequence, and repetition. Across all of the categories, one common theme emerges: time spent early in the system design cycle can lead to great economy savings over a system lifecycle.at later stages. System designs can be 50 to 200 times less expensive to fix early with firm, executable requirements than months later when the system parts are being integrated and problems are found[34].

Waterfall design model

In the traditional “Waterfall” sequential design process, RE progress is seen as flowing steadily downwards (like a waterfall) and is illustrated in Figure 3.

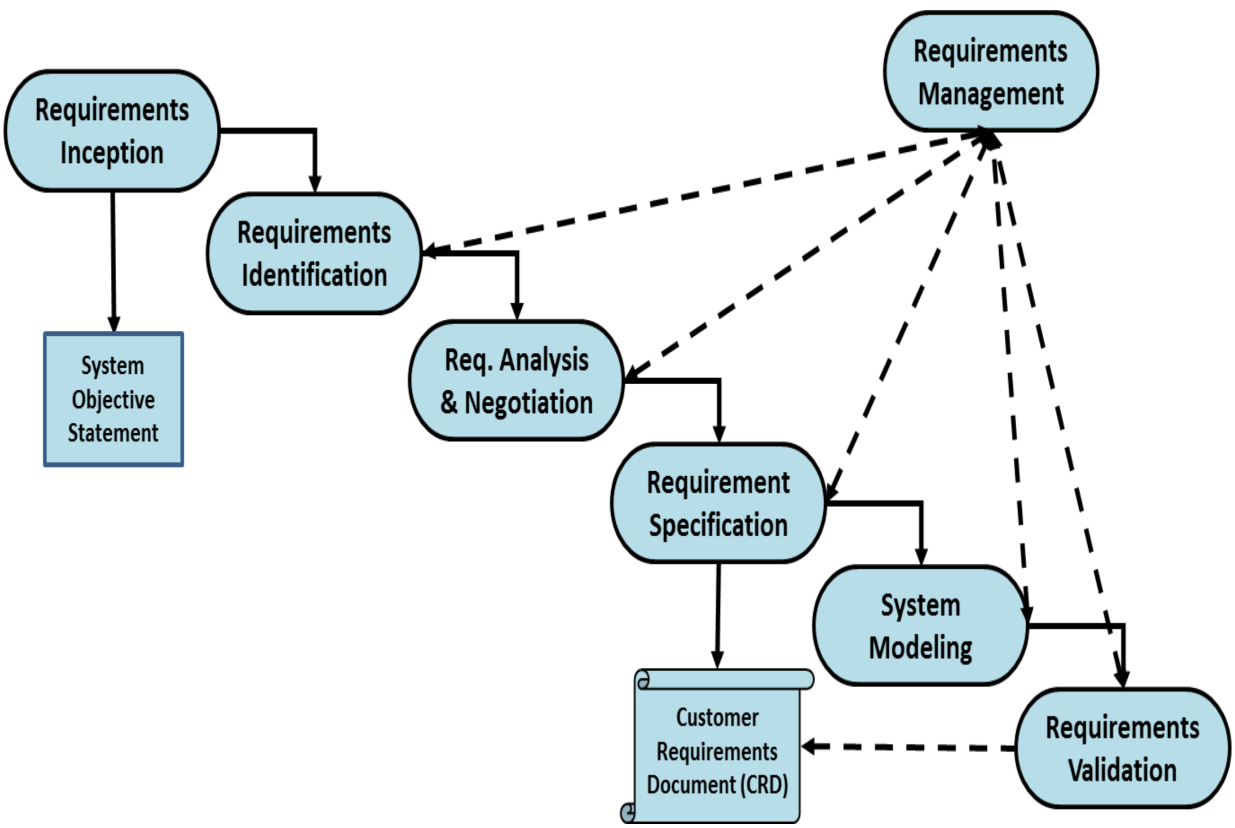


Figure 3: Traditional “Waterfall” RE strategy

The waterfall development model originates in the manufacturing and construction industries were highly structured physical environments in which after-the-fact changes are prohibitively costly, if not impossible[36]. Companies which outsource projects typically employ a traditional waterfall process to generate a solid set of requirements for the outsourced project contractor to employ[37]. The first formal description of this model is often cited in a 1970 article by Winston W. Royce[38].

Within the Waterfall design process, system design requirements are firmly set before system design modeling begins, requiring limited interaction between the PM's system design team and the future customers of the product. This often occurs as "requirements given from on high" within an organization and the system design team is told to use the specified requirements to begin the design process. If the waterfall RE phase is done badly (and this is often the case when the business confuses shoddy requirements with faster progress) or the requirements are allowed to evolve, the waterfall method delivers failure or costly re-work, as the end result will only ever be as good as the specifications[39].

Spiral design model

In the more conventional "Spiral" iteration design process, the structure is similar to the "Waterfall" sequential design process, but with a key difference illustrated in Figure 4: the ability to cycle back to an earlier stage when questions arise or requirements are modified to meet a changing customer need. The spiral approach required high levels of interaction between the PMs system design team and the customers intending to use the new product. The iterative development model evolved from the software development community where highly dynamic development environments grapple with the abstract and near "invisible" nature of software[40].

Within a spiral strategy, system design requirements and systems models are iterated back and forth between the customers and the PM's system design team. While more dynamic and interactive, "spiral" RE strategies have the problem of locking down requirements as "good enough" to initiate actual system design.

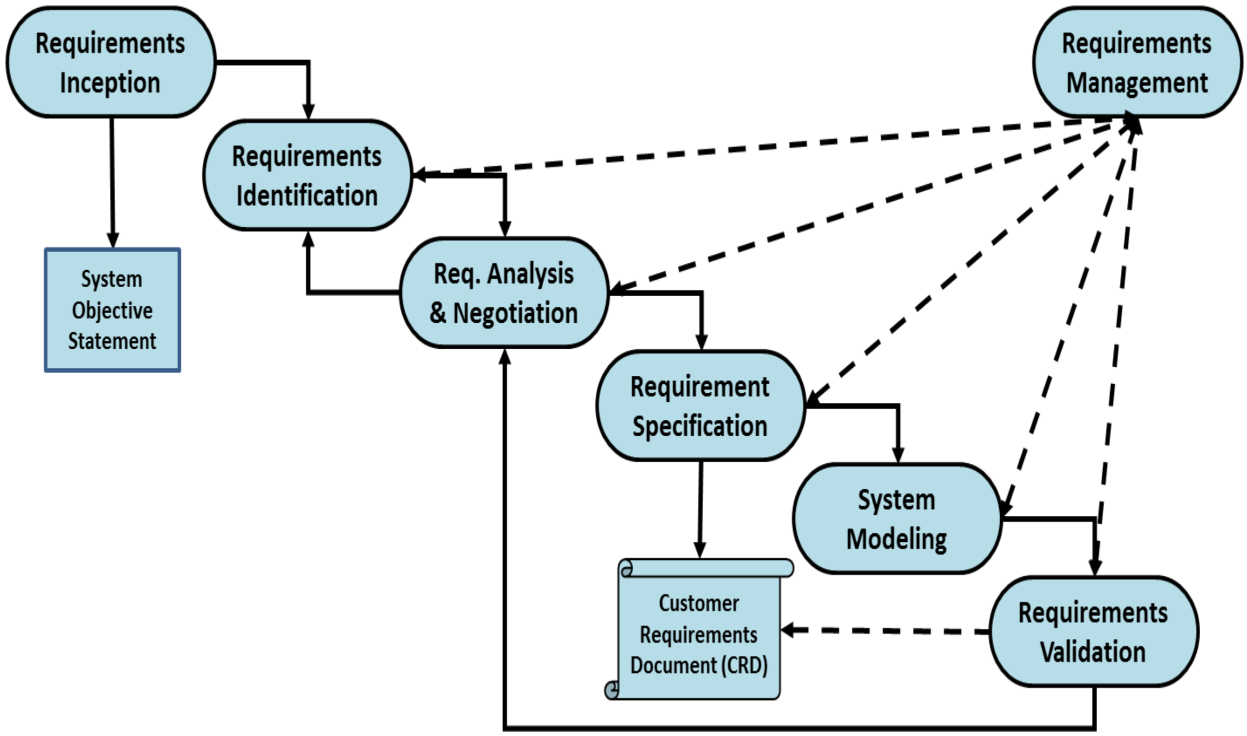


Figure 4: Example RE "Spiral" strategy

Incremental design model

Where the "waterfall' and "spiral" RE development strategies have specific problems with their implementation, the "staged" or iterative strategy combines the best of both earlier strategies while trying to minimize their associated problems.

The basic idea behind this strategy is to develop a system design through repeated cycles (iterative) and in smaller portions at a time (incremental), allowing system design teams to take advantage of what was learned during development of earlier parts or increments of the system[41]. Requirements are iterated and streamlined to identify critical thresholds and provide initial capability. Additional requirements are identified and developed to provide added capability that builds on the existing capability. Learning comes from both the development and use of the system, where possible key steps in the process start with a simple implementation of a threshold set of the system requirements and iteratively enhance the evolving versions until the full system is implemented[42].

A “staged” or iterative strategy delivers an initial capability to the customer in a timely manner. Issues potentially arise from the customer not getting “the full deal” at once (managing customer expectations) and continuing to secure funding to develop additional system incremental upgrades. The incremental design strategy is illustrated in Figure 5.

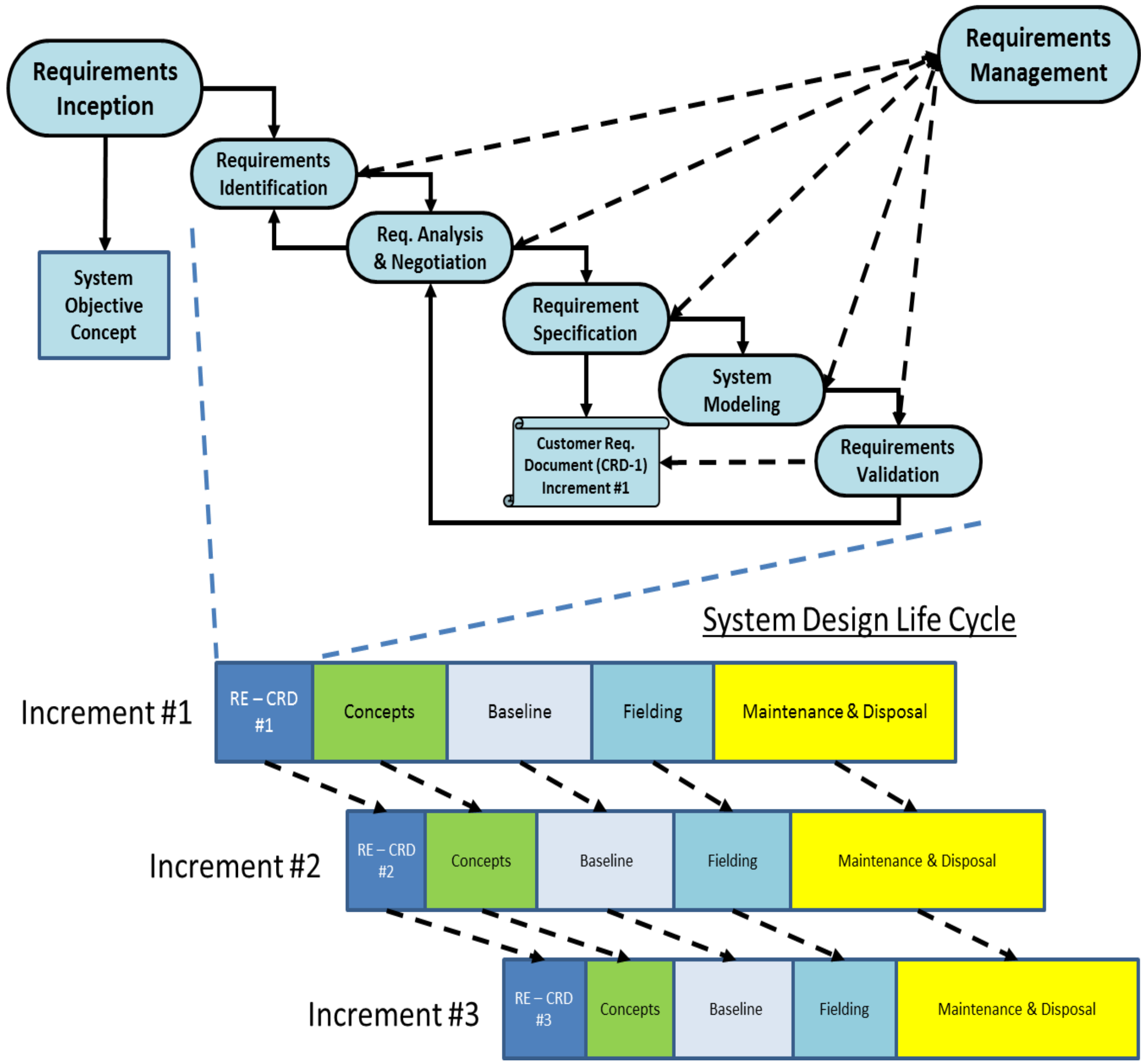


Figure 5: Example RE incremental strategy

2.2.3 Requirement generation methods

Some specific means of requirement generation and solidification utilized by the strategies of RE are summarized next.

1. Traditional techniques: Covers a broad class of individual generic data gathering techniques including questionnaires, surveys, interviews and analysis of existing documentation[43].
2. Group elicitation techniques: Covers general group data gathering with the aim to foster customer agreement and buy-in. These include brain-storming, focus groups, and joint requirement development workshops to elicit requirements, analyze their details and uncover cross-functional implications[44].
3. Model-driven techniques: Attempts to conceptually design the customer's needed system, with the help of a planning support system which serves as an education base and a planning guide for the customer. Through the user interface and the integration process, the customer can develop a detailed and reliable list of requirements[45].
4. Requirements Triage: Is a fast paced method for selecting the requirements which are aligned with the overall business/customer goals and discard others as early as possible[46].
5. Goal modeling: Considers how the project's intended system meets organizational goals, why the system is needed and how the stakeholders' interests may be addressed. Usually, a composed list of requirements are merely clues and "why?" is repeatedly asked to the customer until the actual business purposes are discovered[47].

2.2.4 Database generation

As a key subcomponent of the RE process, system models require technical data input to effectively test requirements within a system design. This technical data, when placed into a software database, allows software to access the data for key tasks like model evaluation and sorting. Without correct (verified) data that is properly used (validated) within a system model, any analysis, optimization or application will be rendered unreliable.

In general, data verification and validation is used to evaluate whether data has been generated according to specifications, satisfy acceptance criteria, and are appropriate and consistent with their intended use. Data verification is a systematic process for evaluating performance and compliance of a set of data when compared to a set of standards to ascertain its completeness, correctness, and consistency using the methods and criteria defined in the project documentation. Data validation follows the data verification process and uses information from the reference documentation to ascertain the usability of the data in light of its measurement quality objectives and to ensure that results obtained are scientifically defensible[48].

For the STMI process, the database will hold key information on each technology being evaluated for inclusion into the modeled system design. This includes performance, cost and schedule data that has been referenced from industry sources (verified) and is appropriate for the system model being employed (validated).

Performance Data

Typically, Key Performance Parameters (KPPs) of the system design are identified during the RE process and are included as factors in the technology database (i.e. material properties of density, strength and unit cost). When the SMEs are preparing the technology database, technology performance factors need to be referenced and applicable to the system being designed.

Technologies considered for the database must have achieved a level of maturity to offer a demonstrated capability. On the “Technology Readiness Level (TRL)” scale developed by DoD and NASA, and adopted by industry, DoD program offices tend to start investing in technologies that are TRL-4, and integrating technologies that are TRL-6 or higher[49]. Therefore the STMI database must consist of technology items that are TRL-4 (in development) to TRL-9 (fielded and commercially available). Additional discussion on TRL ratings will be conducted in the strategic technology planning, section 2.4.5.

Cost and schedule estimation

Estimates of cost and time required achieving the systematic steps to a TRL-6 ranking and documenting lifecycle costs are a central pivot point for the STMI database and successful STMI process execution. All the cost estimates must also be verified and validated for use in the planned system design. Optimistic or biased estimates vs. ones linked to historical and engineering estimates can significantly skew the results of the optimized technology mix. The World Wide Web provides an enormous wealth of time and cost estimation guides based on technology or market areas from reputable government agencies and peer reviewed periodicals (i.e. energy[50], construction[51], and nuclear power[52] for example). DOE G 430.1-1 (1997)[53] and Ereev & Patel (2012)[54] provide some additional guidelines for estimating specialty costs like R&D maturation and production. Additional “rules-of-thumb” can be applied to help balance the engineering estimate to account for the “unknown-unknowns” (many government offices use % “safety factors” against the engineering estimates that are based on the TRL level and SME experience).

2.2.5 RE placement within the STMI process

For STMI stage one, RE steps 1-6 are negotiated between the customer and PM team and results in the initial CRD being presented, database generated and system models prepared. RE step 7 is an ongoing process that will often reinitiate steps 1-6 in preparation to execute STMI to examine future requirements that change on the system design. So, in a practical since, STMI will be applying the staged or incremental design approach with the ability to rapidly conduct trade studies and requirements analysis with the customer.

2.3 Value Engineering

Formalized by the DoD in 1963, Value Engineering (VE) is a fundamental approach which challenges decisions at every level of a design lifecycle and takes nothing for granted. It is applicable to systems, equipment, facilities, procedures, methods, software, and supplies. VE may be successfully introduced at any point in the lifecycle of the product under consideration while improving quality-related features such as durability, reliability, and maintainability[55]. As part of this literature review, the background of VE will be explored. Then VE implementation and applicability to the STMI process will be examined.

2.3.1 VE background

The term Value Engineering was developed during World War II and is widely used in industry and government, particularly in areas such as defense, transportation, construction, and healthcare[56]. The Office of Federal Procurement Policy Act, 1996, requires every federal agency to maintain a VE program[57], and DoD, taking cues from industry, has had an active VE program since the early 1960s[58]. The federal government's application of VE to projects, processes, and products has demonstrated success, saving a reported $1 billion per year in-house and $250M per year through contractor-led efforts[59].

VE is defined as "an organized effort directed at analyzing the functions of systems, equipment, facilities, services and supplies for the purpose of achieving the essential functions at the lowest lifecycle cost consistent with required performance."[60] It is an effective technique for reducing system costs, increasing productivity, and improving overall quality.

2.3.2 VE methodology

In the early portion of a system's lifecycle, VE is directed toward analyzing the functions under development. In this respect, it differs from most other cost reduction techniques, were some other techniques may reduce inherent quality by cheapening the product to reduce cost. The VE technique starts with a determination of the required system design functions, identifies the customer threshold requirements to meet that function and then seeks lower cost alternatives to achieve that essential function. The objective is to identify and eliminate unnecessary cost without loss in needed customer requirements, quality or reliability.

Typically, customer requirements go through an extensive vetting process (as described in the section 2.2 RE discussion). The minimal level a requirement must meet is typically denoted as the "threshold" level. Once the minimal capability has been satisfied, customers often will have an "improved" requirement that is a goal or "objective" to be reached. VE focuses only on the "threshold" requirement values to meet the required minimums that a system is required to perform. Future design reviews with VE to meet "objective" requirement levels must be recompleted, as trade studies or incremental improvement designs, and have the documented understanding that requirement thresholds are no longer in operation.

The lifecycle of a system or equipment begins with the determination that an operational deficiency exists or a new capability is needed. Figure 6 illustrates a common situation in which the savings potential decreases as the program ages[61].

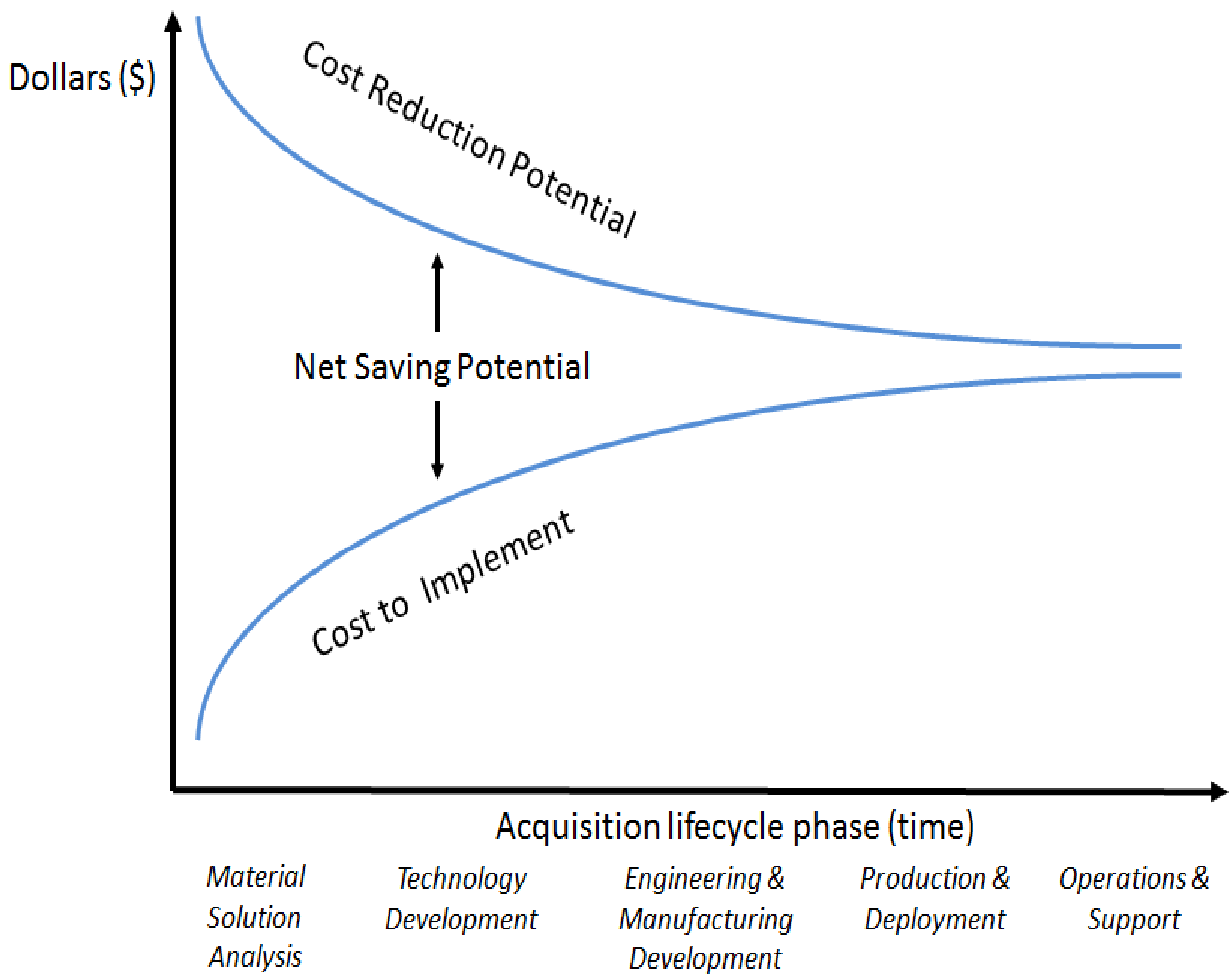


Figure 6: Lifecycle VE savings potential

Early VE tends to produce greater savings or “cost avoidance” for two reasons. First, more actions of the PM’s system design are affected by the savings actions. Second, earlier changes lower implementation costs such as testing, modifications to production lines, retooling expenses, and changes to operational support elements (e.g., spares, manuals, maintenance facilities, etc.). Therefore, it is more cost effective to implement VE as early as possible in the system lifecycle.

The DoD VE framework has developed eight phases to VE implementation with specific questions addressed at each point. A summary of the standard VE phases and questions addressed[62] are included in Table 2. As VE is implemented, it is directed toward analyzing the functions of a system or process to determine "best value," or the best relationship between worth and cost. This process is illustrated in Equation 1-4, where i = each system of technologies which meets the threshold requirements[63].

Equation 1: $\text{Worth}_i = (\text{DevelopmentCost}_i + \text{UnitCost}_i)$

Equation 2: MinWorth = System with least expenditure (worth) to provide Threshold functionality

Equation 3: $\text{LifecycleCost}_i = \text{DevelopmentCost}_i + \text{UnitCost}_i + \text{MaintenanceCost}_i + \text{OperationsCost}_i + \text{DisposalCost}_i$

Equation 4: “BestValue$_i$” Function (f) = $\frac{\text{MinWorth}}{\text{LifecycleCost}_i}$

System “worth” is basically the cost to develop and acquire the capability. Lifecycle costs generally include any cost to the system, from its “birth” to its “death” when it is disposed of or taken out of service, including development, acquisition and operations. Equation 3 illustrates the most common lifecycle costs, but additional costs such as facilities, storage, testing, certification, or company overhead can be incorporated as separate entries. In some cases, the disposal cost can be negative when there is a salvage value for the system. The “best value" is represented by a design or system that consistently performs the required basic function meeting customer requirements and has the lowest lifecycle cost.

Table 2: VE phases and questions to address

VE Phase	Questions Addressed	STMI process
Orientation	What is to be studied?	System selected for analysis
Information Gathering	What is it? What does it do? What does it cost? What is it worth?	• State system objective • Specify customer requirements • Identify primary components and supporting technologies • Identify existing systems, capabilities and costs
Speculation	What else will do the job?	• Database generation • Identify alternate technologies
Analysis	What do the alternatives cost? Which is least expensive?	• Research technology development to reach TRL-6 • Establish maturation costs • Establish acquisition costs • Establish operations costs
Development	Will the proposed alternative work? Will the proposed alternative meet requirements? What will the proposed alternatives require?	• Model alternate technologies placed into system design • Identify worth of technologies meeting user requirements
Presentation	What is recommended? What are the alternatives? What will it cost? How much will it save? What is the implementation schedule?	• System design optimization based on “best value” • Generate technology development schedule • Cost to mature selected technologies for TRL-6 system inclusion
Implementation	Who is responsible for implementation? What actions have to be taken? Established completion dates? Have requirements for progress reporting been established?	• Recommendation to PM team • Compare system design to existing commercial systems
Follow-up	Did the idea work? Did it save money? Could it benefit others?	• Sensitivity analysis • Incremental delivery

Because "costs" are measurable, "cost reduction" is often thought of as the sole criterion for a VE application. However, the real objective of VE is "value improvement," and that may not result in an immediate cost reduction. For example, facilities construction can yield a better value over the lifecycle when construction is approached in a manner that incorporates low maintenance, environmentally-sound and energy-efficient practices and materials, but the initial facility cost might be higher. Therefore, in addition to cost savings, VE often yields system lifecycle benefits such as: improved performance, relative ease of repair and replacement, repeatable manufacture, standardization or simplification of operations, lighter weight, and improved use of resources[64]

Although worth and cost can each be expressed in monetary units, BV is a dimensionless expression of the relationship of these two with a “perfect” BV score equaling a value of one.

2.3.3 STMI VE implementation

The VE phases, questions and best value analysis are implemented in the first and second stage of the STMI process. VE forms the core selection process for determining technology selection within the system design and laying out the technology development schedule for the STP. Early VE implementation integrates well into the STMI process, focusing on early STP technology maturation.

2.4 Optimization and metaheuristic optimization methods

Once Requirements Engineering and Value Engineering have identified promising technologies to incorporate into their system design, how does a PM differentiate between potentially thousands of technology options? How does one rank the good, bad and the ugly technologies at their current TRL while trying to meet customer primary requirements, manage your development budget and do it quickly if options change? The answer lies with choosing an optimization method to examine the value engineering objective function and generate a best option for the computational time allowed.

An all option optimization, "brute force" optimization is usually the first choice of analysts looking to examine initial technology combinations with a computer, since a simple series of programming loops to examine all of the technology combinations is usually straight forward to program. Where this method insures finding the optimum technology combination, it also is computationally intensive and can take a long time to process if the numbers of options are considerable. PMs may not have the luxury of time to have their technology optimizer examine all of the possible combinations in this manner.

Another option is to employ metaheuristic algorithms which offer the ability to find an acceptable solution quickly. Metaheuristics provide an excellent means to search complex problems such as STMI technology development challenges. First, the research reviews a developmental history of metaheuristics. Then current techniques are summarized. Finally, current implementations are examined for optimum use by the STMI process.

2.4.1 Metaheuristic background

Researchers, developers and operators have always had to balance computational efficiency and computational accuracy when attempting to solve complex optimization problems. One way this balance manifested itself was with the beginning of metaheuristic methods in the early 1950's when researchers examined non-gradient methods to solve optimization problems with objective functions that were not continuous or differentiable[65]. These real world objective functions tended to be highly non-linear, incorporated multiple factors and were under complex constraints, making them very lengthy and difficult to solve with calculus based differentiation. Metaheuristics brought in a compromise methodology which offered reduced computational time to yield a "good" solution vs. other computational methods which could require infinite or very long times to compute an optimal solution. The actual term "metaheuristic" was created by Fred Glover in his paper "*Future paths for integer programming and links to artificial programing"* in 1986[66], and actually incorporates two important parts of a computational optimization methodology used to evaluate candidate solutions to these complex objective functions.

The first part, or the “heuristic”, is derived from the Greek term “heuriskein” for "find" or "discover,"[67] and it essentially means to “find by trial and error”[68]. The basic operation of a heuristic is to intensely examine a localized area and identify the best local solution. Therefore, a heuristic might not always find the best or global optimum solution, but it can guarantee to find a good local solution. Techniques like hill climbing[69], gradient methods[70] or neighborhood evaluation[71] generate a local optimization “good solution” where the heuristic methodology tends to stop due to its inability to climb out of local minima/maxima and check other points in the global solution space.

The second part, or “meta”, from the Greek preposition “μετά” for "after" or "beyond"[72] offers an overarching guidance strategy or algorithm. This algorithm allows diversification and provides the underlying heuristics the ability to check multiple areas of a solution space and reduce the probability of getting “stuck” in local minima/maxima condition. This overarching algorithm becomes a random or semi-guided method for global optimization of the solution space. Some basic “meta” examples include random search[73], iterated local search[74] and population methods[75].

Overall, metaheuristic algorithms are essentially elaborate combinations of local search, and randomization with a global algorithm which directs the sampling of the solution space[76]. New algorithms often incorporate combinations of earlier methods to improve solution performance and continue to adapt them for specific problem sets. Metaheuristic methods offer means to improve the quality of problem solutions within a reasonable time over a global solution space, but there is no guarantee that the optimal solution will be found in the allowed computational timeframe.

The following section of this chapter provides an overview of common metaheuristic methods in use today. Since new variations are constantly being developed to improve solution speed and accuracy, this review should be considered a starting point for future study and potential application. Table 3 provides a selection of current academia textbooks dealing with metaheuristics as an additional reference source.

Table 3: A selection of current academic metaheuristic textbook references

Author(s)	Title	Publisher	Year
Gendreau, M. and Potiv, J.Y.	Handbook of Metaheuristics	SpringerLink eBooks	2010
Gandibleux, X.	Metaheuristics for Multiobjective Optimization	Springer	2004
Tabli, E.G.	Metaheuristics: from design to implementation	John Wiley & Sons	2009
Glover, F. and Kochenberger, G.A.	Handbook of Metaheuristics	Springer	2003
Yang, X.S.	Engineering Optimization: an introduction with Metaheuristic Applications	John Wiley & Sons	2010
Luke, S.	Essential of Metaheuristics	Http://cs.gmu.edu/~sean/book/metaheuristics	2012
Mitchell, M.	An introduction to Genetic Algorithms	MIT Press	1998
Kennedy, J., Eberhart, R.C. and Y. Shi	Swarm Intelligence	Kaufmann Publishers	2001
Glover, F. and M. Laguna	Tabu Search	Kluwer Academic Publishers	1997

2.4.2 Metaheuristic history

Many problem-solving processes tend to be heuristic throughout human history; however metaheuristics as a scientific method for optimization is a modern phenomenon[77]. Figure 7 provides a graphical timeline[80] of the historical development of Metaheuristics from the 1950's through 2012. From the 1940s to 1960s, metaheuristic methods have been used in various applications. They started simply with pattern search developed by Fermi and Metropolis[78] in 1952 where parameters of the object function were varied with steps taken along the axis of the search-space using decreasing step sizes to narrow the search range. In 1963, Rastrigin[79] demonstrated random search as a means to sample improvements in an object function within a "hypersphere" surrounding the current solution.

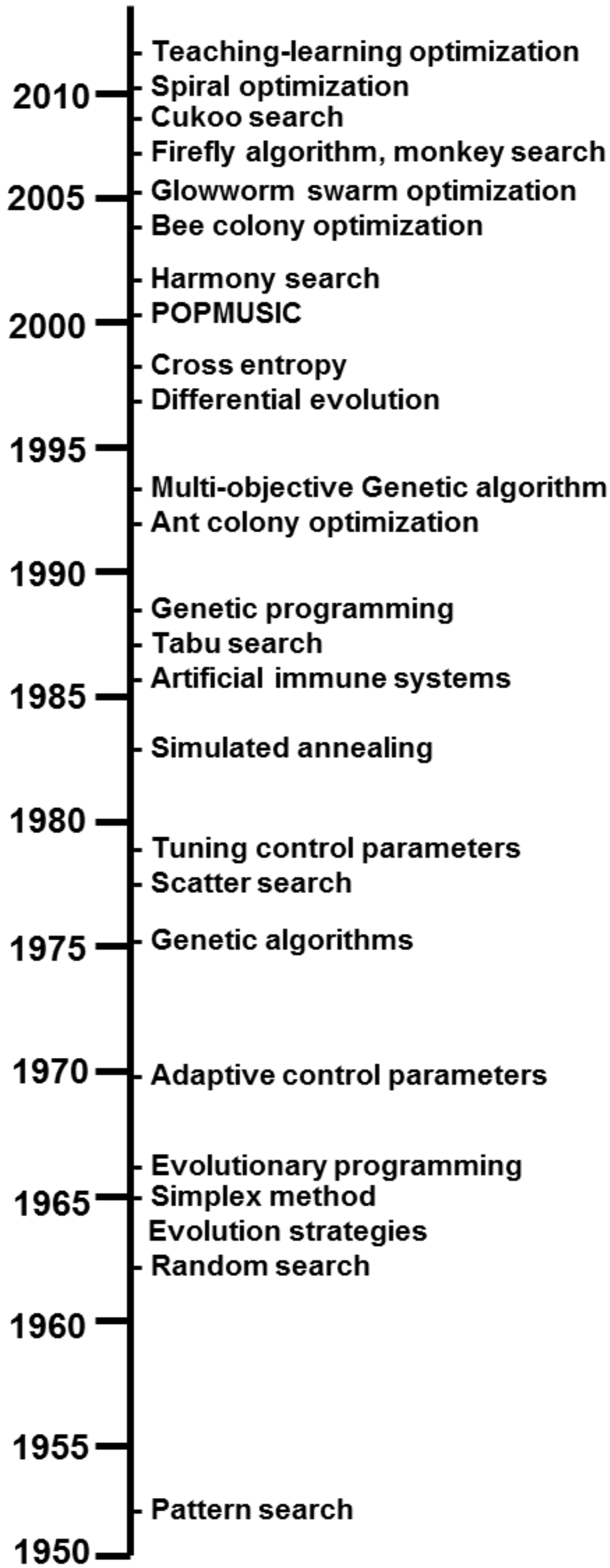


Figure 7: Metaheuristic development timeline

The first breakthrough came with the advent of biological evolution inspired evolutionary algorithms, pioneered by Ingo Rechenberg and Hans-Paul Schwefel[81] in 1963 (evolutionary strategies) and L. J. Fogel et al[82] in 1966 (evolutionary programming). Genetic algorithms (GA) were also developed in the 1960s and 1970s by J. Holland[83], and published in 1975. Each of these methods developed “populations” of candidate solutions to the objective functions, and selection of the next generation of solutions was based on a bias toward improved fitness of the solution. “Parent” solutions generated “children” solutions based on crossover of parent solution “genes” or random “mutations” of the solution “genes”. Each new population generation competed with the old generation in a survival of the fittest or “best” object function solution.

In the 1980s and 1990s development of metaheuristic algorithms began to really accelerate, often inspired by naturally occurring processes. Using an example from industry, S. Kirkpatrick et al[84] developed simulated annealing (SA) in 1983 as an optimization technique inspired by the temperature annealing process of metals. Another important development was the imitation of living organism immune systems by Farmer et al[85] in 1986.

As computing power and memory became more available in the mid-1980’s, the first use of memory allocation in metaheuristics was pioneered by Glover[86] in Tabu search methodology. Tabu search basically retained historical search moves recorded in a Tabu list, and future moves would try to avoid revisiting previous solutions.

The same improvements to computing power were again harnessed in the late 1980’s and 1990’s, developing explorative local search methods which expanded traditional calculus based trajectory methods. These include Greedy Randomized Adapted Search Procedure by Feo and Resende[87], Variable Neighborhood Search by Hanson and Mladenoviĉ[88], Guided Local Search by Voudouris and Tsang[89], and Iterative Local Search by Baxterl[90].

In 1992, Marco Dorigo[91] finished his PhD thesis on optimization and natural algorithms, in which he described his innovative work on ant colony optimization (ACO). ACO was inspired by the swarm intelligence of social ants using pheromones as a chemical marker for directing solutions toward an optimal path. Also in 1992, John R.

Koza[92] published a book on genetic programming which laid the foundation to revolutionize computer programming. Slightly later in 1995, another significant progress was the development of particle swarm optimization by Kennedy and Eberhart[93]. Around 1996 and later in 1997, R. Storn and K. Price[94] developed their vector-based evolutionary algorithm, called differential evolution (DE). This algorithm proved to be more efficient than genetic algorithms in many applications[95].

At the turn of the millennium, Zong Woo Geem et al[96] developed a music inspired harmony search (HS) algorithm in 2001. In 2002, Pratap et.al.[97] focused on developing a GA technique to handle multi-objective optimization. In 2004, S. Nakrani and C. Tovey[98] proposed the honey bee algorithm and its application for optimizing Internet hosting centers. In 2008, X.S. Yahg et al[99] developed the firefly algorithm (FA). In 2009, Xin-She Yang and Suash Deb introduced an efficient cuckoo search (CS) algorithm, and it has been demonstrated that CS is far more effective than most existing metaheuristic algorithms including particle swarm optimization[100].

During the second decade of the 21st century, metaheuristic developers continued to advance the collective algorithm knowledge through Tamura and Yasuda's spiral optimization[101] and teaching-learning methods proposed by R. Venkata Rao [102].

2.4.3 Metaheuristic algorithms

Metaheuristics are designed to address complex optimization problems where other optimization methods have failed to be effective or efficient in their operation[103]. The following sections describe six prominent metaheuristics optimization methods, ordered by development timeframe, earliest to latest: Genetic Algorithms, Simulated Annealing, Tabu Search, Ant Colony Optimization, Particle Swarm, and Iterative Local Search.

Genetic Algorithms

The term Genetic Algorithm (GA) is a population-based subset of evolutionary computing (EC) which is inspired by nature's capability to evolve a population to adapt to its environment and pass along the genes of the "fittest who survive". Individuals who are more successful in surviving their environment will have a better chance of reproducing, while individuals that are less fit are eliminated. GAs, developed by John

Holland in the 1970s, is based on the biological evolution described by Charles Darwin's theory of natural selection. Holland was the first developer to use crossover (or recombination), mutation and fitness selection for objective function optimization[104]. The basics of GA involve the following steps[105]:

1. Encoding solution set arrays of bits or character strings (chromosomes) for an individual rather than final objective function problem solution. The evolution process is operated over the chromosomes rather than objective function problem solutions.
2. Natural selection becomes the mechanism that relates chromosomes with the efficiency of the problem solution they represent, thus allowing those efficient individuals, which are well-adapted to the environment, to reproduce more often than those which are not.
3. The initial population is usually randomly generated and can be seeded with known good individuals to bias the initial population.
4. The evolutionary process takes place during the reproduction stage. There exist a large number of reproductive mechanisms in Nature. The most common ones are mutation probability (that causes the chromosomes of offspring to be different to those of the parents) and recombination probability (that combines the chromosomes of the parents to produce the offspring).
5. The selection stage picks individuals based on a fitness criteria corresponding to the best solutions in the population. Older, less "fit" individuals are replaced by the newer more fit individuals to create a new population for reproduction.
6. Reproduction and selection stages are repeated until a certain termination criteria is met.

The framework for the GA algorithm process is laid out in the following algorithm.

```
Generate initial population P(0)
t <- 0
WHILE termination conditions not met DO
  Evaluate(P(t))
  P'(t) <- Select(P(t))
  P''(t) <- ApplyReproductionOperators(P'(t))
```

```
  P(t+1) <- Replace(P(t),P''(t))
  t <- t+1
ENDWHILE
Return best solution found
```

Notice that the algorithm establishes a trade-off between the exploitation of good solutions P'(t) (selection stage) and the exploration of new zones of the search space P''(t) (reproduction stage), based on the fact that the replacement policy allows the acceptation of new solutions that do not necessarily improve the existing ones. The GA algorithm, therefore, is an iterative and stochastic process that operates on a set of individuals in a population pool and evaluates cycles of population reproduction based on the fitness criteria and is illustrated in Figure 8. This fitness criteria value is the quantitative information the algorithm uses to guide the search.

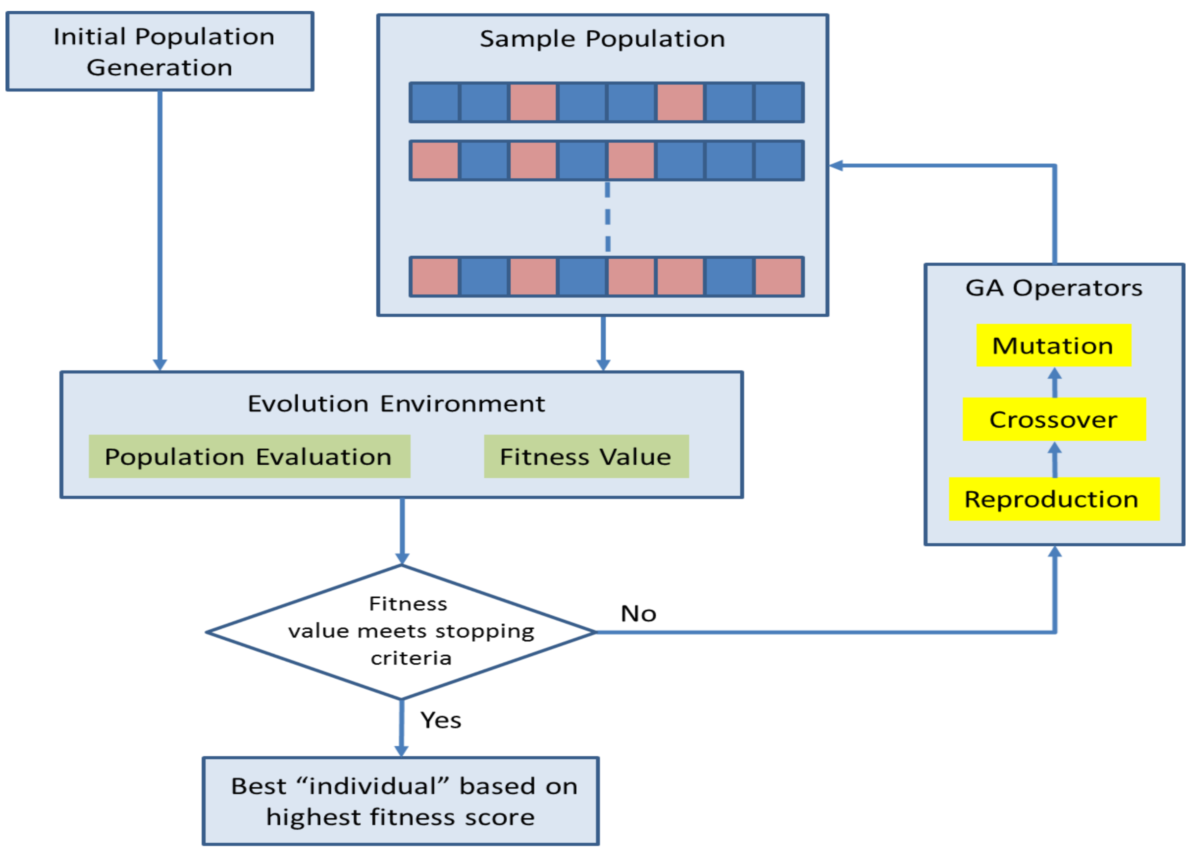


Figure 8: GA evolution flow

Simulated Annealing

Simulated Annealing (SA) is the oldest among the metaheuristics with an explicit strategy to avoid local minima. The origins of the algorithm are in statistical mechanics (Metropolis algorithm), and it was first presented as a search algorithm for optimization problems in 1983 by Kirkpatrick et al[106]. The fundamental idea is to allow moves resulting in solutions of worse quality than the current solution (uphill moves) in order to escape from local minima. The probability of doing such a move is decreased during the search. A visualization of SA is shown in Figure 9 and can be described by dropping a set of ping-pong balls onto a global solution set display of the objective function. Initially, the ping-pong balls have "high energy" to bounce up and out of local minima points. As the energy decreases, the ping-pong balls eventually settle into points of deeper or globally optimal minima locations[107].

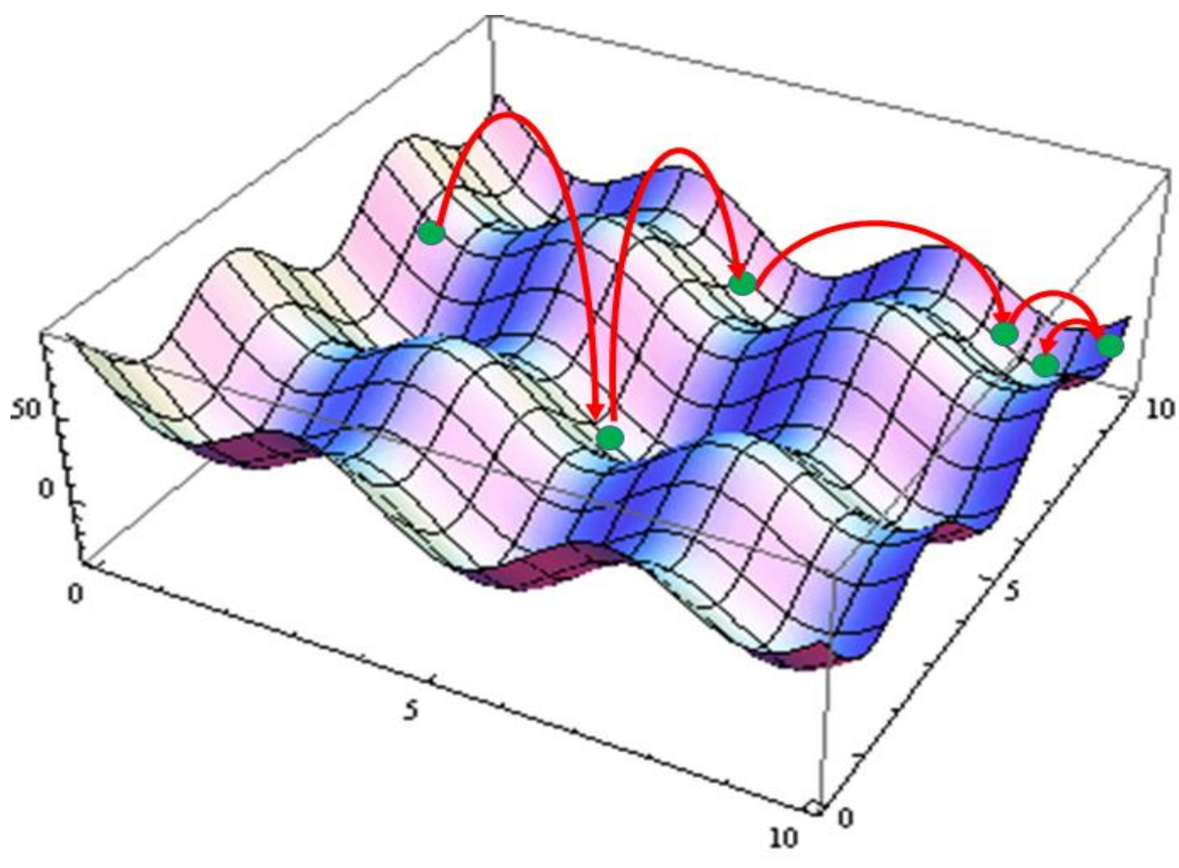


Figure 9: SA operation visualization

The framework of the SA metaheuristic is shown next in an algorithm example and incorporates two search strategies: global random walk and a local iterative improvement.

```
s := GenerateInitialSolution()
T := T_0
WHILE termination conditions not met
  s' := PickAtRandom(N(s))
  IF f(s') < f(s)
    s := s'
  ELSE
    Accept s' as new solution with probability p(T,s',s)
  ENDIF
  Update(T)
ENDWHILE
```

The algorithm starts by generating an initial solution (either randomly or heuristically constructed) and by initializing the so-called energy or temperature parameter *T*. Then the following is repeated until the termination condition is satisfied: A solution *s'* from the neighborhood *N(s)* of the solution *s* is randomly sampled, and it is accepted as new current solution depending on objective function *f(s), f(s')* and *T*. The temperature *T* is decreased during the search process, thus at the beginning of the search the probability of accepting uphill moves is high and it gradually decreases, converging to a simple iterative improvement algorithm. This process is analogous to the annealing process of metals and glass, which assume a low energy configuration when cooled with an appropriate cooling schedule.

In the first phase of the search, the bias toward improvements is low and it permits the exploration of the search space. This erratic component is slowly decreased thus leading the search to converge to a (local) minimum. The probability of accepting uphill moves is controlled by two factors: the difference of the objective functions and the temperature. The choice of a cooling schedule for T is crucial for the performance of the algorithm. Small increment cooling schedules, like those that follow logarithmic law in Equation 5, can guarantee convergence to a global optimum, but are typically too slow and impractical for analysis applications. Fast converging cooling schedules, like those following geometric law in Equation 6, are usually adopted in applications where near global optimums are acceptable.

Equation 5: $T_{k+1} = \Gamma/\log(k+k_0)$ were k_0 is a constant

Equation 6: $T_{k+1} = \alpha T_k$

Overall, cooling schedules and initial temperatures must be adapted to the particular problem being examined[108], since the “energy” cost of escaping from local minima depends on the structure of the objective function landscape being searched.

SA is often used to solve discrete, combinatorial optimization problems, but can exceed the time for a complete search of the solution space if the energy (annealing) schedule is extended[109].

Tabu Search

Coined in the same paper where Glover introduced the term metaheuristic in 1986[110], Tabu Search (TS) explicitly uses the history of the search (memory), both to escape from local minima, and to implement a global search strategy. The adaptive memory feature of TS allows the implementation of procedures that are capable of searching the solution space economically and effectively.

The framework for TS is shown next in an algorithm example.

```
k := 1
s := GenerateInitialSolution()
s* := s;
WHILE the termination criteria not met DO
  Identify N(s). (Neighbourhood set)
  Identify T(s,k). (Tabu set)
  Identify A(s,k). (Attribute set)
  Choose best s' from N(s,k) = N(s)-T(s,k)+A(s,k).
  s := s'
  IF f(s') < f(s*) THEN
    s* := s'
  ENDIF
  k := k+1.
END WHILE
```

Since local choices are guided by information collected during the search, TS contrasts with memoryless designs that heavily rely on semi-random processes that implement a form of sampling. The emphasis on responsive exploration (and hence purpose) in TS, whether in a deterministic or probabilistic implementation, derives from the supposition that a bad strategic choice can often yield more information than a good random choice. The TS emphasis on short-term, adaptive memory makes it possible to exploit the types of strategies that underlie the best of human problem-solving, instead of being confined to mimicking the processes found in lower orders of natural phenomena and behavior[111]. Figure 10 illustrates the local optimum and strategic "non-optimum" path choices to explore the solution space[112].

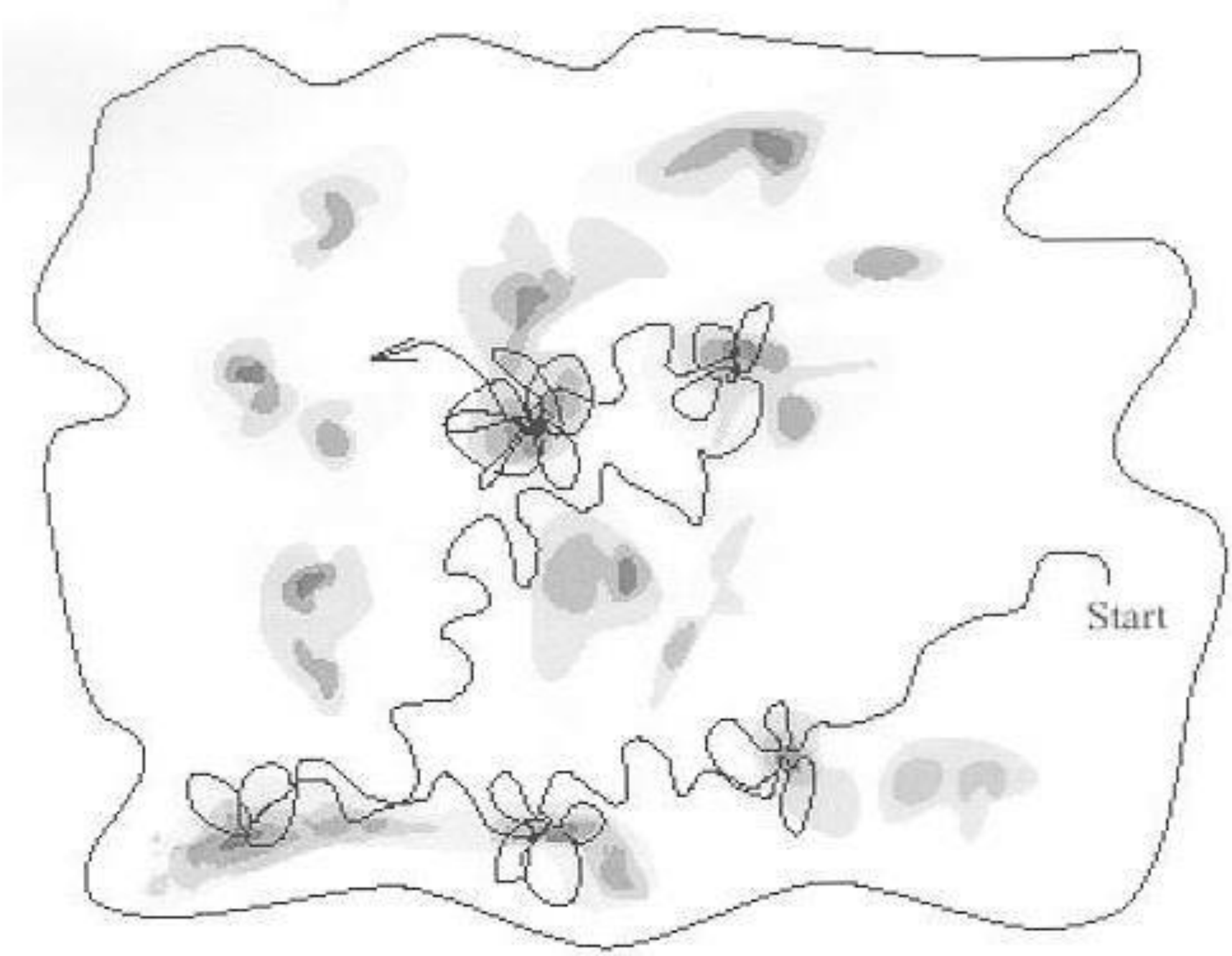


Figure 10: Sample exploration path for TS in a potential solution space

The length of the tabu list controls the memory of the search procedure. Shorter tabu lists will force the search to concentrate on small areas of search space, where longer lists will explore larger regions since they forbid revisiting a higher number of solution attributes. The short-term memory is implemented as a tabu list set (T) that keeps track of the most recently visited solutions and forbids moves toward them. The neighborhood (N) of the current solution is thus restricted to the solutions that do not belong in the tabu list. Instead of recording full solutions, attributive memory structures (A) are based on recording attributes. This type of memory records information about solution properties (attributes) that change in moving from one solution to another.

After each iteration, the best solution from the tabu set is chosen as the new current solution. The use of the tabu list prevents the search from returning to recently visited solutions and therefore prevents endless cycling within the algorithm. TS can be used for solving combinatorial optimization problems, but the size of the tabu list must be tuned for each optimization problem explored since it impacts the solution quality and computational time[113].

Ant Colony Optimization

Ant Colony Optimization (ACO) is a metaheuristic approach proposed by Marco Dorigo in 1992[114] and is based on the foraging behavior of real ants following "pheromone" trails to food sources. Ant colonies in nature consist of individual members who interact with each other and their environment to ensure the survival of the colony by finding food sources. When ants attempt to find short paths between their colony and food sources, they communicate indirectly by using pheromone to mark the decisions they made when building their respective paths. As more ants follow the same route, additional layers of pheromone are put in place, creating a favored path. Thus, some favored routes emerge, which are often the shortest or most efficient ones to a food source and the ant colony nest.

In ACO, artificial ants search for good solutions to an optimal "food source" location. Starting from an initial random foraging routine, the routes are updated with a pheromone concentration that decays at a constant rate. When new ants decide about a direction to go, they choose with higher probability paths that are marked by stronger pheromone concentrations as depicted in Figure 11 where "a" is the exploration path and "b" is the return path of the "foraging" ant going from the food source (F) and the ant colony nest (N) leaving an increasingly stronger pheromone path[115,116].

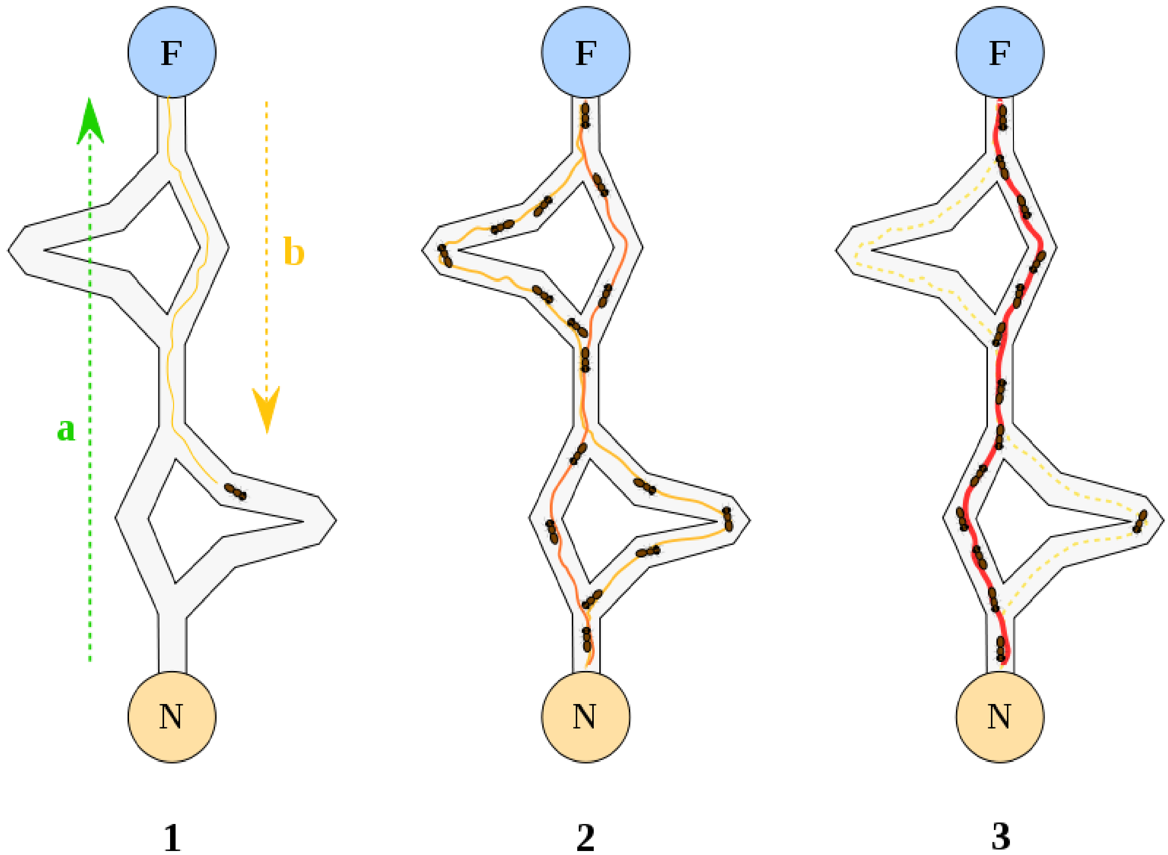


Figure 11: Ant Colony Optimization pheromone routing

Afterwards, the next iteration of ants builds path solutions with the updated pheromone information. When a constrained combinatorial optimization problem is considered, the problem constraints are built into the ants' foraging procedure in such a way that in every step of the path construction process only feasible solution components can be added to the current partial solution[117]. This basic foraging behavior, tied with path constraints, is the basis for a cooperative interaction which leads to the emergence of shortest paths to an optimum solution.

The framework of the ACO metaheuristic is shown next in an algorithm example. It consists of three parts gathered in the *ScheduleActivities* construct where these three activities are scheduled and synchronized by the algorithm designer.

```
InitializePheromonevalues
WHILE termination conditions not met DO
  ScheduleActivities
    AntBasedSolutionConstruction()
    PheromoneUpdate()
    DaemonActions() {optional}
  END ScheduleActivities
ENDWHILE
```

AntBasedSolutionConstruction(): An ant constructively builds a solution to the problem by moving through nodes of the construction graph. Ants move by applying a stochastic local decision policy that makes use of the pheromone values and the heuristic values on components and/or connections of the construction graph. While moving, the ant keeps in memory the partial solution it has built in terms of the path it was walking on the construction graph.

PheromoneUpdate(): When adding a component c_i to the current partial solution, an ant can update the values of the pheromone trails that were used for this construction step. This kind of pheromone update is called online step-by-step pheromone update. Once an ant has built a solution, it can (by using its memory) retrace the same path backward and update the pheromone trails of the used components and/or connections according to the quality of the solution it has built. This is called online delayed pheromone update. Another important concept in Ant Colony Optimization is pheromone evaporation. Pheromone evaporation is the process by means of which the pheromone trail intensity on the components decreases over time. From a practical point of view, pheromone evaporation is needed to avoid a too rapid convergence of the algorithm toward a sub-optimal region. It implements a useful form of forgetting, favoring the exploration of new areas in the search space.

DaemonActions(): Daemon actions can be used to implement centralized actions which cannot be performed by single ants. Examples are the use of a local search procedure applied to the solutions built by the ants, or the collection of global information that can be used to decide whether it is useful or not to deposit additional pheromone to bias the search process from a non-local perspective. As a practical example, the daemon can observe the path found by each ant in the colony and choose to deposit extra pheromone on the components used by the ant that built the best solution. Pheromone updates performed by the daemon are called offline pheromone updates.

ACO is well suited for optimization of dynamic, multi-objective, stochastic, continuous and mixed-variable optimization problems that can be run and adapted to changes in real-time[118].

Particle Swarm Optimization

Particle swarm optimization (PSO) is a population-based stochastic approach developed by Eberhart and Kennedy in 1995[119], inspired by social behavior of bird flocking or fish schooling. PSO shares many similarities with evolutionary computation techniques such as Genetic Algorithms (GA). The system is initialized with a population of random solutions and searches for optima by updating generations that are attracted toward the current global best solution and its own best known location, while exhibiting a tendency to move randomly[120]. However, unlike GA, PSO has no evolution operators such as crossover and mutation. PSO maintains a single status population that responds to new discoveries about its solution space. PSO belongs to the class of swarm intelligence techniques that are used for solving continuous and discrete optimization problems[121].

In PSO, simple software agents, called particles, are initially set to move randomly in the search space of an optimization problem. The position of a particle represents a candidate solution to the optimization problem at hand. The movement of a swarming particle consists of a stochastic component and deterministic component. At each iteration, each particle searches for better positions or “fitness” in the search space by changing its velocity vector base on these components by “emulating” successful neighbors. Each particle is attracted toward the position of the current global best solution and its own best known location, while exhibiting a tendency to move randomly[122].

The framework of the PSO is shown next in an algorithm example and its mimicking of natural operations like birds and fish[123,124] are illustrated in Figure 12.

```
RandomlyGenerateInitialPopulation
WHILE termination conditions not met DO
  ParticleFitnessEvaluation
  UpdateGlobalFitness+Location
  UpdateParticleVelocity+Postion
ENDWHILE
```

The PSO framework consists of three parts: fitness evaluation of each particle, global update and particle update. Fitness evaluation is conducted by supplying the candidate solution to the objective function. Individual and global best fitness and positions are updated by comparing the newly evaluated fitness against the previous individual and global best fitness, replacing the best fitness and positions as necessary. The velocity and position update step is responsible for the PSO optimization ability[125].

Figure 12: Natural swarming behavior of birds and fish

Iterative Local Search Optimization

Iterative Local Search (ILS) is a trajectory based method that combines local search and perturbations of the solution around the local minima, as illustrated in Figure 13[126]. The basic technique was developed by Baxter in 1981 and summarized by Lourenço, et al[127] in 2003. The essential idea of Iterated Local Search lies in focusing the search not on the full space of solutions but on a smaller subspace defined by the solutions that are locally optimal for a given optimization engine.

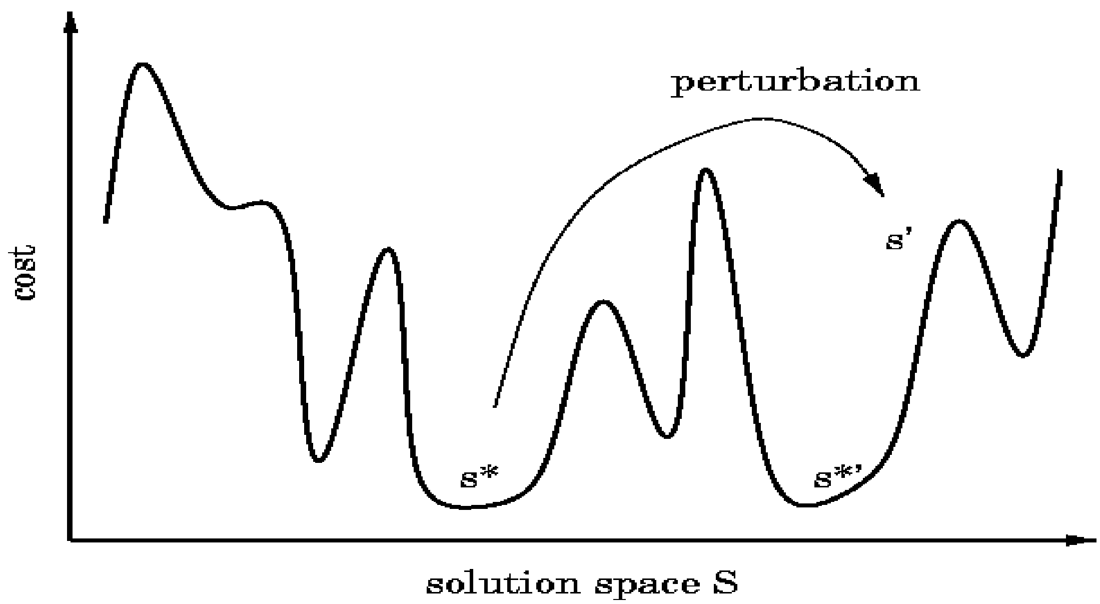


Figure 13: Graphical illustration for ILS

The potential power of ILS lies in its biased sampling of the set of local optima. The efficiency of this sampling depends both on the kinds of perturbations and on the acceptance criteria. Interestingly, even with the most naive implementations of these parts, ILS is much better than random restart. Much better results can be obtained if the ILS modules are optimized. First, the acceptance criteria can be adjusted empirically as in simulated annealing without knowing anything about the problem being optimized. Second, the Perturbation routine can incorporate as much problem-specific information as the developer is willing to put into it. In practice, a rule of thumb can be used as a guide: a good perturbation transforms one excellent solution into an excellent starting point for a local search. A sample framework for ILS is provided next in an algorithm example.

```
  s=GenerateInitialSolution
  s*=ExecuteLocalSearch(s)
WHILE termination conditions not met DO
  s' = Perturbation(s*,history)
  s^'=ExecuteLocalSearch(s')
  s^=ApplyAcceptanceCriterion(s^,s^',history)
ENDWHILE
```

ILS explores the search of local minima (denominated as *S**) with respect to some given embedded heuristic, called LocalSearch. ILS achieves this heuristically as follows. Given the current *s**, we first apply a change or perturbation that leads to an intermediate state *s′* (which belongs to *S*). Then LocalSearch is applied to *s′* and we reach a solution *s*′* in *S**. If *s*′* passes an acceptance test, it becomes the next element of the walk in *S**; otherwise, one returns to *s**. The resulting walk is a case of a stochastic search in *S**, but where neighborhoods are never explicitly introduced. This ILS procedure should lead to good biased sampling as long as the perturbations are neither too small nor too large. If they are too small, one will often fall back to *s** and few new solutions of *S** will be explored. If on the contrary the perturbations are too large, *s′* will be random, there will be no bias in the sampling, and we will recover with a random restart type algorithm.

Iterated Local Search was designed for and has been predominately applied to discrete domains, such as combinatorial optimization problems. For these problems, ILS iterates values for discrete variables until the stopping conditions are satisfied[128].

2.4.4 Metaheuristic applications

Table 4 provides a sampling of current metaheuristic method applications. This is not an all-encompassing list of applications, but a selection of industry, engineering and design examples to give the reader a flavor of areas that have been explored with these metaheuristic methods.

Table 4: Common metaheuristic methods and sample applications.

Metaheuristic Name	Metaheuristic Type	Author(s)	Application
Genetic Algorithm (GA)	Naturally inspired, population based	Altshuler and Linder, 1997[129]	Wire antenna EM property designs
		Beasley, et al, 2001[130]	Aircraft airport routing
		Benini and Toffolo, 2002[131]	Design of wind turbines for electrical power
		Giro, et al, 2002[132]	Electrically conductive carbon materials
		Howley, 1996[133]	Spacecraft orientation maneuvering
		Keane and Brown, 1996[134]	Orbital structures load bearing truss
		Kewley and Embrechts, 2002[135]	Military tactical planning
		Mahfoud and Mani, 1996[136]	Financial market predictions
		Obayshi, et al, 2000[137]	Supersonic vehicle wing design
		Porto, et al, 1995[138]	Sonar acoustics recognition software training
		Sambridge and Gallagher, 1993[139]	Earthquake hypocenter location
		Sato, et al, 2002[140]	Acoustics of concert halls
		Schechter, 2002[141]	Diesel engine design and efficiency
		Williams, et al, 2001[142]	Satellite orbital placement and spacing
Simulated Anealing (SA)	Physics inspired, Trajectory with a random walk	Benvenuto, et al, 1992[143]	Digital filters
		Brünger, et al, 1997[144]	X-ray crystallography
		Dougherty and Maryott, 1991	Groundwater management
		Emden-Weinert and Proksh, 1999[146]	Airline crew scheduling
		Fan and Machemehl, 2006[147]	Transit routing
		Kolahan, et al, 2007	Structural optimization
		Sarker and Yao, 2003[148]	Manufacturing batch sizing
		Spinellis and Papadopoulos, 2000[149]	Product line buffering
		Wilson and Cui, 1990[150]	Bipolymer-peptide design

Table 4**:** Common metaheuristic methods and sample applications, continued**.**

Metaheuristic Name	Metaheuristic Type	Author(s)	Application
Tabu Search (TS)	Trajectory with memory	Betttinger, et al, 1997[151]	Timber harvest scheduling
		Crainic, et al, 1993[152]	Supply chain allocation
		Drezner, et al, 2001[153]	Financial predictions
		Gendreau, et al, 2010[154]	Vehicle dispatch/routing
		Hubscher and Glover, 1994[155]	Multiprocessor scheduling
		Laguna, et al, 1993[156]	Job scheduling
		Muthuselvan, et al, 2009[157]	Power control systems
		Reves, 1993[158]	Machine sequencing
		Zhang, et al, 2009[159]	Image retrieval
Ant Colony Optimization (ACO)	Naturally inspired, population based	Doerner, et al, 2004[160]	Investment management
		Hani, et al, 2007[161]	Industrial layout
		Kumar, 2007[162]	Disaster relief logistics
		Levine and Ducatelle, 2004[163]	Inventory
		Parpineli and Lopes, 2002[164]	Data mining
		Rizzoli, et al, 2007[165]	Vehicle routing
		Serra and Venini, 2006[166]	Plane truss design
		Shyu, et al, 2004[167]	Job shop scheduling
		Sim, 2002[168]	Network routing
Particle Swarm Optimization (PSO)	Naturally inspired, population based	Alrashidi and El-Hawary, 2009[169]	Electrical power systems
		He, et al, 2004[170]	Mechanical design
		Juang, 2004[171]	Network design
		Liao, et al, 2005[172]	Flow shop scheduling
		Liu, et al, 2006[173]	Architectural design
		Mahmoud, et al, 2007[174]	Electronic beam steering
		Miranda and Fonseca, 2002[175]	Power distribution
		Omran, et al, 2002[176]	Image classification
		Robinson, et al, 2004[177]	Electromagnetic antenna
		Venter and Sobieszczanski-Sobieski, 2004[178]	Transport aircraft wing design
Iterated Local Search (ILS)	Trajectory with perturbation	Besten, et al, 2001[179]	Single machine scheduling
		Blum, 2007[180]	Software code design
		Cordón and Damas, 2006[181]	Image processing
		Dirk, et al, 2005[182]	Communications
		Dong, et al, 2009[183]	Multi-stage production schedule
		Vansteenwegen, et al, 2009[184]	Team orienteering schedule
		Walker, et al, [185]	Vehicle Routing

2.4.5 Metaheuristic application for STMI

Due to the complex, non-continuous nature of the technology populations examined, and the non-linear objective functions explored in the initial development of the STMI process, parallels to reviewed GA applications in Table 4 have been noted. This research therefore explored a detailed Genetic Algorithm (GA) search optimization algorithm in Chapter three. By using a system design objective functions and VE based "best value" as the fitness criteria, GA appeared to be well suited for a fast, deterministic global solution set optimization. Since the GA code can generate slight variations to the "optimal solution" due to the random nature imbedded within the population generation, Beasley & Chu (1996)[186] recommends averaging at least 10 runs to establish the reliability of the objective function used within the GA. In an eventual research or business implementation, averaged answers of the GA STMI optimizer would be tested against the "All case" analysis to assess the objective function's overall reliability and accuracy.

2.5 Strategic Technology Planning

In the past 15 years, Strategic Technology Planning (STP) has evolved from a senior level "art" to a more rigorous and systematic process. First, a background review on strategic technology planning purpose and standard Technology Readiness Levels (TRLs) notations are presented. Then current technology planning capabilities will be examined. Finally, current strategic technology planning techniques are noted were applied within the DoD acquisition framework, illustrating STMI applicability.

2.5.1 STP background

The companies and DoD programs that will survive and succeed in the future will be those that plan and manage their technology planning process, deriving a business benefit from it. Federal entities like the DoD have not effectively planned or managed their technology planning processes. Too many times DoD programs have slipped schedule or overrun costs due to immature (<TRL-6) technologies driving system designs[187]. The U.S. Government Accountability Office (GAO), which watches over the fiscal performance of federal programs, has reported that in the past, numerous DoD

acquisition programs have failed to adequately plan their technology developmental decisions and rely on immature information to make key system design decisions[188]. The GAO has stated that TRL-6 is the risk reduction target plateau that subsystem technologies must reach prior to program offices integrating them into full system prototyping, as outlined in the GAO report NSIAD-99-162[189]. In response to these findings, the DoD has revamped its primary instruction (DODI) document to conduct DoD acquisition programs. This instruction, the new DoDI 5000.2, was published 08 December 2008 and places a stronger emphasis on maturing technologies earlier in the "pre-system acquisition" portion of a program lifecycle[190] and requiring TRL-6 or greater matured technologies into formal system acquisition.

The standard notation for tracking technology development is based on DoD's TRLs[191]. Originally developed by NASA in the 1990's[192], DoD adopted the notation in 2001[193] as a common means to assist new technology development and improve communication among technology developers through a common reference set. They provide a systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology[194]. This consistency provides a significant input to risk assessment dealing with incorporating a technology into a system design.

TRL rankings have been traditionally assigned to the developing technologies and tracked as they mature. Each TRL, starting at basic research ideas (TRL-1) to mature and producible technologies (TRL-9), have key development milestones which differentiate each maturation level. Technology maturation therefore can be carefully tracked and identified at each level, with the common reference points. TRLs have been applied by industry and multiple branches of the Federal government for the past 15+ years.

Table 5 is taken from the "DoD Technology Readiness Assessment Deskbook (2005)" and provides a TRL summary[195]. Table 6 provides the common TRL assessment definitions[196].

Table 5: TRL descriptions

TRL	Description
1. Basic Principles	Basic scientific research begins to be translated into applied R&D
2. Technology concept and/or application formulated	Invention begins. Designs are limited to analytical studies. Applications are speculative and there may be no proof or supporting detailed analysis
3. Analytical and experimental critical function and/or characteristic proof-of-concept	Active R&D is initiated. Analytical and laboratory studies are initiated to validate predictions of separate elements of the technology that have not yet been integrated
4. Laboratory environment validation of technology components and/or breadboard	Basic technological components are integrated to establish that they will work together in the lab.
5. Relevant environmental validation of component and/or breadboard	High fidelity integration of technological components with realistic supporting elements tested in a relevant, high fidelity laboratory environment or simulated operational environment.
6. Relevant environmental demonstration of a system or sub-system model/prototype	Representative integrated model or prototype tested in a relevant, high fidelity laboratory environment or simulated operational environment.
7. Operational environmental demonstration of system prototype	Prototype near or at planned operational system operating in an operational environment such as an aircraft, vehicle, ship or space.
8. Actual system completed and qualified through test and demonstration	Technology has been proven to work in its final form and under expected conditions. Developmental test and evaluation of the system has been conducted to determine if the technology meets design specifications.
9. Actual system proven through successful mission operations	Actual application of the technology in its final form and under mission conditions like those encountered in Operational Test and Evaluation.

Table 6: TRL clarifying definitions

Term	Definition
BREADBOARD:	Integrated components that provide a representation of a system/subsystem and which can be used to determine concept feasibility and to develop technical data. Typically configured for laboratory use to demonstrate the technical principles of immediate interest. May resemble final system/subsystem in function only.
HIGH FIDELITY:	Addresses form, fit and function. High fidelity laboratory environment would involve testing with equipment that can simulate and validate all system specifications within a laboratory setting.
LOW FIDELITY:	A representative of the component or system that has limited ability to provide anything but first order information about the end product. Low fidelity assessments are used to define trend analysis.
MODEL:	A reduced scale, functional form of a system, near or at operational specification. Models will be sufficiently hardened to allow demonstration of the technical and operational capabilities required of the final system.
PROTOTYPE:	The first early representation of the system which offers the expected functionality and performance expected of the final implementation. Prototypes will be sufficiently hardened to allow demonstration of the technical and operational capabilities required of the final system.
RELEVANT ENVIRONMENT:	Testing environment that simulates the key aspects of the operational environment.
SIMULATED OPERATIONAL ENVIRONMENT:	Environment that can simulate all of the operational requirements and specifications required of the final system or a simulated environment that allows for testing of a virtual prototype to determine whether it meets the operational requirements and specifications of the final system.
OPERATIONAL ENVIRONMENT:	Environment that addresses all of the operational requirements and specifications required of the final system to include platform/packaging.

2.5.2 Strategic technology planning methods

Various methods for STPs identified in literature and their use in the sample DoD acquisition lifecycle are reviewed in this section and summarized in Table 7.

<u>*Technology Roadmapping*</u>

This is a structured, manual technique best applied pre-MS-B to visualize when technology is being matured and initially integrated into a preliminary design. Technology roadmapping is widely used within industry, with 26% of the companies aware of the process and 10% actively engaged in the year 2000[226]. The generic technology roadmap is a time-based chart used to develop, represent and communicate strategic plans. The most common roadmap involves planning to insert technology into manufactured products. Another highly applicable roadmap is integration planning, which involves the integration and/or evolution of technology as it combines within products or systems. One major drawback occurs when competing technologies are compared with constraints since variables can quickly become multi-dimensional and difficult to visualize as the options increase in complexity[227].

<u>*Science and Technology Strategic Planning*</u>

This method is an overarching manual process that can be applied to individual industries, state governments and DoD to organize pre-MS-B technology planning, resources and leadership support[228,229]. This type of planning assesses existing technical resources and determines whether they can be leveraged better and identifies areas that must be addressed to support technology intensive and driven programs. Key processes include: bringing key stakeholders to develop consensus; providing opportunities for industry, academia, community and government viewpoints; thorough understanding of available industrial and technical resources; identifying performance measures; identifying specific actions, assigned responsibilities and established timelines; being tied to a budgeting process; and finally, having a champion to lead the planning with support from senior leadership to implement the technology strategy in the long term.

Table 7: Problems and solutions in technology planning

Technique	Problem addressed	Solution technique
Technology roadmapping[197]	Aligning knowledge assets and management with business objectives	Knowledge asset roadmap
	Implementing design project planning strategy	Program planning roadmap
	Insertion of technology into manufactured products	Product planning (Philips) roadmap
	Integration and evolution of advanced technology	Integration planning roadmap
	Long-range planning	Integrated manufacturing technology roadmap
	Strategic planning	T-plan roadmap
	Technology to support organizational capabilities	Service/capability planning roadmap
TDS[198]	Long-term technical data requirements	Data management strategy
	Manpower and functional competency requirements	Time-phased workload assessment
Dynamic strategic planning	Electric vehicle policy planning[199]	- Vehicle performance models - Spreadsheet simulation and sensitivity analysis - Manual probability estimates and decision analysis
	Semiconductor industry-wide strategic technology plan[200]	- Hierarchical decision models - Sensitivity analysis
System optimization	Parallel maturation of advanced spacecraft system component technologies[201]	- Manual selection of system risk reducing options - Genetic algorithm to “auto select” risk reducing options
	System readiness levels[202]	Evolutionary algorithms
Production scheduling	Integrated process planning/ production scheduling[203]	Integrated Process Planning/ Production Scheduling (IP3S)
	Job shop scheduling[204]	Genetic algorithms
	Medium-range production scheduling in a multi-product batch plant[205]	Large-scale mixed-integer linear programming

Table 7: Problems and solutions in technology planning – continued-

Technique	Problem addressed	Solution technique
Investment planning / capacity management	Capacity acquisition, planning and replacement[206,207]	- Regenerative dynamic programming - Multi-stage integer programming
	Capacity investment decisions[208,209]	- Best-response functions with Markov-perfect Nash equilibrium - Stochastic capacity-portfolios
	Evaluating investments in production technology[210]	- Large-scale linear programs - Mixed-integer programming - Stochastic dynamic models - Heuristic solutions
	Expansion and equipment replacement[211]	Heuristics and linear programming
	Justification and implementation of Advanced Manufacturing Technologies[212]	Statistical survey data analysis with linear regression relationships
	Long-term capital investment planning[213]	Advanced queuing network model
	Optimal management of capacity[214]	Two period capacitated Cournot game
	Production technology installation[215]	Mixed-integer program with bilinear objective
Inventory management	Available manufacturing capability[216]	Decision support system base on linear programming
	Inventory requirements planning[217]	Decision support tool with heuristic approach
	Launch vehicle availability[218]	Integer linear programming
	Tactical capacity planning[219]	Advanced queuing network model
Supply chain management	Allocation to global supply sites[220]	Mixed integer program with multi-commodity network flow
	Large-scale supply chain optimization[221]	Mixed integer program with supporting heuristics
	Optimal allocation of business to suppliers[222]	REV, an industry-independent optimization-based market-clearing tool
	Supply chain networks[223]	Multi-echelon inventory optimization
	Supply chain performance[224]	Multi-echelon inventory optimization
	Supply network production and distribution[225]	Mixed integer program with bilinear objective

Dynamic Strategic Planning

A process of using OR techniques combined with computer simulation and manual analysis methods, Dynamic Strategic Planning[230,231], can help identify strategic plans for the development and implementation of early technology policy agreed to by all involved stakeholders. Evolving from traditional systems analysis and decision analysis, Dynamic Strategic Planning is used to develop technology or large scale engineering projects from objectives, including a technically efficient plan prepared through optimization or simulation methods and an evolution of the plan over time. Dynamic Strategy Planning is best suited to help planners prepare a technology plan prior to the selection of a specific technology system required for a detailed system design.

Technology Development Strategy

The Technology Development Strategy (TDS) is a manual DoD process outlined in DoDI 5000.2, that is drafted after the MS-A. The TDS documents the technology risk reduction and determines the appropriate set of technologies to mature and integrate into a full system. The TDS includes a rationale for the selected acquisition strategy, cost estimates, development schedule, performance goals and specific exit criteria to advance a system design beyond the Technology Development Phase.

System Optimization

Once a system design and specific technology capabilities have been approved at MS-B, system optimization becomes a priority, involving the interaction of multiple technologies to form a functioning product. Two current types of system optimization involve minimizing the overall risk of system components to drive the system design[232] and optimizing the "system readiness level (SRL)" of a design maturity[233]. Both methods utilize OR methodologies like generic and evolutionary algorithms to optimize system design elements.

Investment Planning/Capacity Management

As the system design is being completed and integrated, post MS-B focus begins to shift toward production of the new product. The DoD and manufacturers must evaluate investments in production technologies to best manage the production and stockpiling of parts for maturing system designs. These long-term decisions establish the overall level of resources and extend over a time horizon long enough to obtain resources. Capacity decisions affect the production lead time, operating costs and industry's ability to compete. Standard OR methodologies are often applied including Mixed-Integer programming, heuristics and network models.

Production Scheduling

Once the final product design has been completed and initial prototypes have demonstrated manufacturing capabilities, the ramp-up to full production begins. Planners must allocate the available production resources over time to best satisfy stakeholder criteria. DoD stakeholders typically specify delivery time, quantity, and quality confirmations. Industry stakeholders want to minimize cost, meet schedules and deliver a product that meets customer expectations. OR techniques of scheduling optimization involve meeting a set of tasks to be performed, performing tradeoffs between early and late completion of a task, and balancing inventory for the task with frequent production changeovers.

Inventory Management

As low rate production is approved post MS-C, "Inventory" is one of the more visible and tangible aspects of doing business and maintaining production. Raw materials, goods in process and finished goods all represent various forms of inventory. In a literal sense, inventory refers to stocks of anything necessary to produce a product. These stocks represent a large portion of the business investment and must be well managed in order to maximize profits. Unless inventories are controlled, they are unreliable, inefficient and costly[234].

Supply Chain Management

As production is initiated during Low Rate Initial Production (LRIP), the management of the supply network involves all movement and storage of raw materials, work-in-process inventory, and finished goods from point of origin to point of consumption. Supply Chain Management is the systemic, strategic coordination of the traditional business functions and the tactics across these business functions within a particular company and across businesses within the supply chain, for the purposes of improving the long-term performance of the individual companies, material flow and the supply chain as a whole[235].

Placed in context with the new DoDI 5000.2 program acquisition lifecycle depicted in Figure 14, early technology planning (TRL 1-3) usually involves a manual process, like technology roadmapping, or using Operation Research (OR) based dynamic strategic planning tools. These early planning tools are used to forecast user needs and identify key technology components to develop for a Material Development Decision (MDD). Initial planning strategies help develop basic Research and Development (R&D) plans to fill technology gaps and to lay out overall strategies for management and maturation of the technology[236], stepping from basic research ideas (TRL-1) to active research (TRL-3). These technologies are identified from multiple sources including academia, government labs and commercial industry conductioning R&D activities.

At the completion of the MDD, the PM's office conducts manual technology roadmapping and builds a Technology Development Strategy (TDS). This manual effort to evaluate the multitude of technology options is to help guide the technology maturation from TRL-3 to prototyped TRL-6 technologies for inclusion into the initial system design. Once the technologies have been developed and matured sufficiently to TRL-6, a PM can employ additional OR techniques and begin to assist with system integration and maturation during the product's Engineering and Manufacturing Development phase. As the matured system approaches production, OR based investment evaluation or planning is used to optimize the best production level technology capacity improvements. Later in a product or program lifecycle, additional OR methodologies help technology intensive users focus on real problems involving testing, production, scheduling, inventory management and material supply chain management.

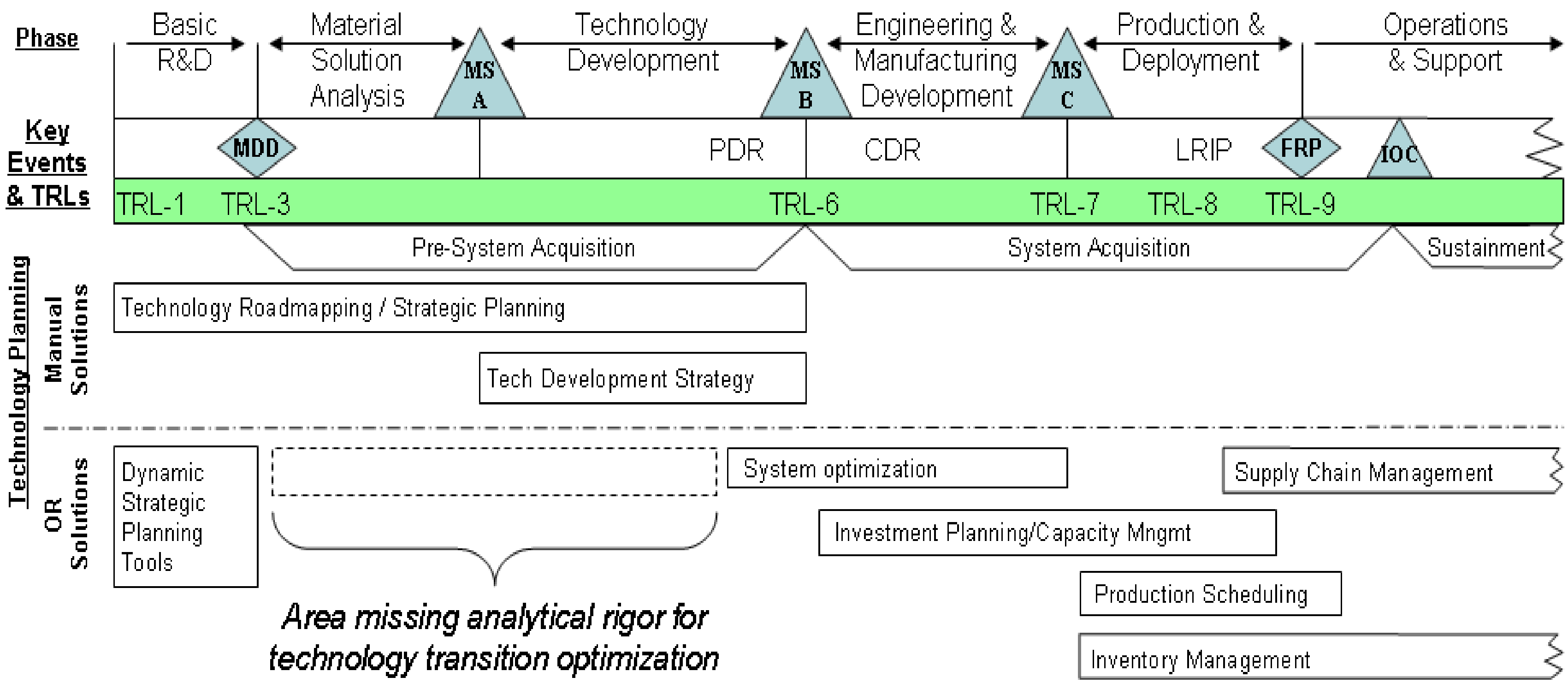


Figure 14: DoD acquisition "lifecycle" with STP

2.5.3 STMI applicability

Current applications for Strategic Technology Planning (STP) are summarized and placed in typical areas with respect to the DoD acquisition lifecycle and TRL ratings in Figure 14. Laying out the current STP applications also denotes a key finding in that there appears to be little or no published OR type analysis occurring to help bridge the TRL-4 to TRL-6 technology maturation “chasm”. This discovery led to the foundation of this research - to develop a STMI process to fill this analytical OR “hole” for technology planning, transition and maturation.

2.6 Post-process analysis options for STMI

2.6.1 Trade-off analysis

A tradeoff analysis (also called a trade study) is an analytical method for evaluating and comparing system designs based on customer-defined criteria. Trade-offs are always based on the constraints of the system design. Many factors go into the decision to sacrifice schedule, cost or performance, and it is not always possible to change one without affecting the others[237].

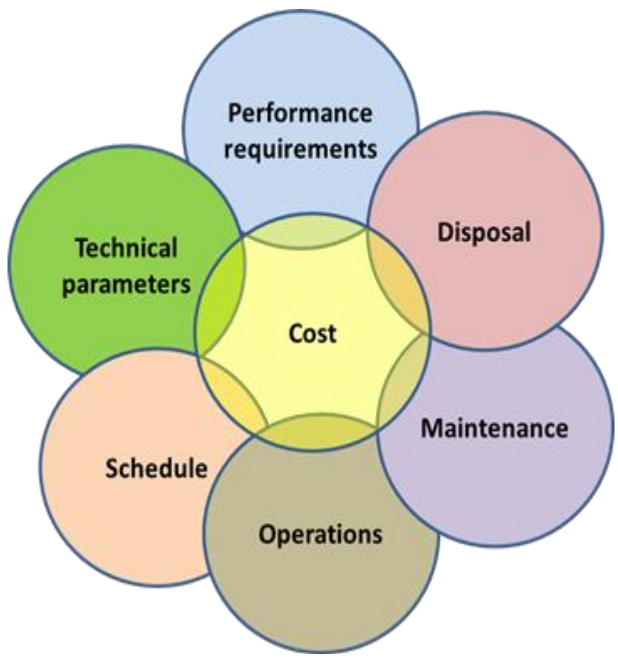


Figure 15: Trade off analysis operators

In the broadest sense, a trade-off is giving up one thing to get another. Some choices entail trade-offs, while others do not. Choices that do not entail trade-offs we’ll call optimization choices. Examples of trade-offs could be:

- Increasing a development budget to reduce the development time (although this is usually not linear)

- Increasing the development time to stretch out the development budget into multiple fiscal years
- Substituting lower cost materials without changing the project specifications
- Depot or frontline maintenance
- Smaller, constellation units or larger omnibus unit
- Upgradeable or replacement

Tradeoff studies are important because[238]:

1. They create an objective mechanism for evaluating systems
2. They document the decision process
3. The preference structure is quantified
4. The tradeoff study process educates the customer
5. They help validate system requirements by providing a measurable quantity that helps determine if and how well a design satisfies the requirements[239]
6. They assist in selecting the preferred alternative

2.6.2 Data and requirement sensitivity analysis

All PMs have had to make program decisions where there was uncertainty about key factors that where relevant to the decision process (technology performance, schedule, costs, and funding). This "decision making under uncertainty" occurs when the information needed to make a decision is incomplete, potentially inaccurate, or just educated guesses**.** Risk management becomes the means to identify, assess and prioritize the effects of uncertainty on a decision maker's objectives[240]. A powerful tool available for risk management analysis is the field of sensitivity analysis, which can give the PM an indication of how sensitive one or more of the factors within the system design are to uncertainties in their value.

Sensitivity analysis is very useful when attempting to determine the impact on the actual outcome if a particular variable differs (i.e. uncertainty) from what was previously assumed as a baseline. By creating a given set of scenarios, the analyst can determine how changes in one variable(s) will impact the target variable. The analyst can also establish a range of values for the object value coefficients where the optimal values of the decision variable will not change[241]. This is also known as the “relevant range[242]” or “range of optimality of the input coefficients for a specific output decision variable.

There the many methods for conducting sensitivity analysis like graphical analysis[243,244], scatter plots[245], variance-based methods[246,247] and screening[248,249]. One of the simplest and most common approaches to sensitivity analysis is that of changing of factors to see what effect this produces on the output[250]. Two common methods are one-variable-at-a-time (OVAT) and a multifactor approach called Design of Experiments (DoE).

OVAT customarily involves moving one input variable, keeping others at their baseline (nominal) values, then returning the variable to its nominal value, and repeating for each of the other inputs in the same way. Sensitivity may then be measured by monitoring changes in the output, e.g. by range analysis, partial derivatives or linear regression. This appears a logical approach as any change observed in the output will unambiguously be due to the single variable changed. Furthermore, by changing one variable at a time, one can keep all other variables fixed to their central or baseline values. This increases the comparability of the results (all ‘effects’ are computed with reference to the same central point in space) and minimizes the chances of computer program crashes, which is more likely when several input factors are changed simultaneously. OVAT is frequently preferred by modelers because of practical reasons, as it is easy and fast. In case of model failure under OVAT analysis the modeler immediately knows which input factor is responsible for the failure[251].

Despite the simplicity of the OVAT approach, it does not fully explore the input space, since it does not take into account the simultaneous variation of input variables. This means that the OFAT approach cannot detect the presence of interactions between input variables[252]. An option to OVAT is to conduct the sensitivity analysis with a Design of Experiments (DoE) analysis that changes multiple variable at once. DoE allows an analyst to reduce computational time, increase robustness of the analysis, and be able to check variable interactions, especially if more than one input factor is suspected of influencing an output[253].

DoE is a branch of applied statistics deals with planning, conducting, analyzing and interpreting controlled tests to evaluate the factors that control the value of a parameter or group of parameters. Many of the current statistical approaches to designed experiments originate from the work of R. A. Fisher in the early part of the 20th century. Fisher demonstrated how taking the time to seriously consider the design and execution of an experiment before trying it helped avoid frequently encountered problems in analysis. Key concepts in creating a designed experiment include blocking, randomization and replication[254].

Blocking**:** When randomizing a factor is impossible or too costly, blocking lets you restrict randomization by carrying out all of the trials with one setting of the factor and then all the trials with the other setting.

Randomization**:** Refers to the order in which the trials of an experiment are performed. A randomized sequence helps eliminate effects of unknown or uncontrolled variables, including bias.

Replication**:** Repetition of a complete experimental treatment, including the setup.

DoE incorporates purposeful changes to the inputs of a process and an efficient analysis of the corresponding changes to the outputs to accurately predict how the inputs affect the mean and variability of the outputs. A well–performed experiment may provide answers to questions such as:

- What are the key factors in a process?
- At what settings would the process deliver acceptable performance?
- What are the key, main and interaction effects in the process?
- What settings would bring about less variation in the output?

DoE is applicable to both physical processes and computer simulation models and is an effective tool for maximizing the amount of information gained from a study, while minimizing the amount of data to be collected. DoE factorial designs allow estimation of the sensitivity to each factor and also to the combined effect of two or more factors[255].

2.6.3 Incremental improvement studies

An incremental approach produces a working product much earlier than a monolithic approach. The initial reaction to seeing this is usually "This is not what I want", leading to an initial loss of confidence, although the delivery of an increment on time is generally a refreshing change for customers. Confidence is initially high with both incremental and monolithic approaches, but during a lengthy development, customer confidence drops off, as no working product is yet visible. If delivery of the system comes before all confidence is lost, there is hope of recovery, but if confidence goes below a certain point, then no matter how good the system is technically, it will not be accepted by users[256].

If incremental improvements are planned from the start of a project and can be scheduled out as part of a Strategic Technology Plan, showing deliveries and improvements, customers are more willing to get something vs. a single monolithic delivery that may never happen. Keep in mind that the incremental improvements are based on many, small changes rather than the radical changes that might arise from Research and Development. Small improvements are also less likely to require major capital investment than major process changes.

3 Process formulation

Fundamentally, the proposed STMI process is a formalized and repeatable computer based DSS tool which allows PMs to systematically compare and evaluate candidate technology performance for inclusion into a program STP. Utilizing VE principles, STMI generates a recommended STP based on meeting the customer's requirements for an optimized "best value (BV)" technology set. Stage one utilizes RE concepts to document and validate customer requirements and technology database generated as precursors to the formal STMI process in stage two. Stage two is the core of the STMI process. System design objective functions are developed from the user requirements and technology database in stage one, and then used to conduct a VE based best value optimization to identify the best technology set to place in the system design STP. Stage three provides follow-on analysis with the STMI core process to conduct trade studies, sensitivity analysis and incremental improvement studies.

3.1 <u>Stage one: pre-process preparation</u>

3.1.1 Generating an operational concept

The general purpose for an operational concept is to describe to the customers and the development team how the system will function in practice. It describes the main operational concepts, operating environment, and main interactions between the environment and external systems. The operational concept is often illustrated in a graphical representation to depict what the problem is and give an idea of players and operations involved. The graphic gives a quick, high level description of what the concept is supposed to do, and how to do it.

The initial operational concept is useful in establishing the context for a suite of related operational systems. This context may be in terms of options, phase, a time period, a mission and/or a location. By laying out the concept in high level terms, system solutions can be developed to meet the customer's problem. The graphical representation of the operational concept can be used to orient and focus detailed discussions, allowing for a brain storming approach to potential system solutions to evaluate.

In the context for STMI operations, the high level operational concept describes the problem and helps generate many potential solutions at the “Macro” level. A specific system solution can be pulled from the “Macro” level solutions to be evaluated in detail at the “Micro” level. “Micro” level solutions are optimized based on the STMI “best value” which can be lifted up to the “Macro” level system analysis for a final common “best value” analysis and determination of the best overall system concept that meets the customer needs.

Figure 16 and Figure 17 depict a sample “Macro” and “Micro” graphical operational concept for a customer needing a “line-of-sight” aircraft defense against another aircraft during combat. Figure 16 identifies the mission and scope of what needs to be done, and summarizes potential system options to explore.

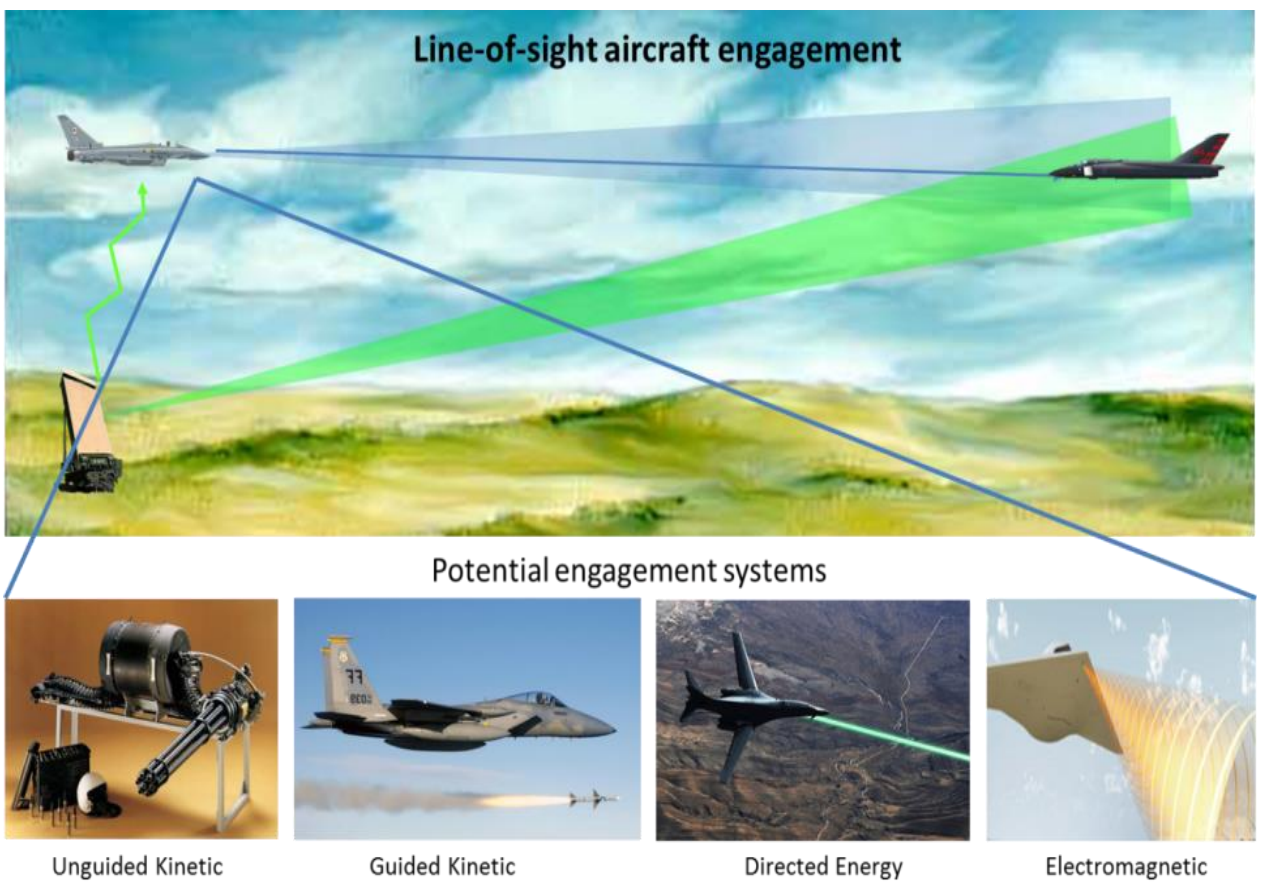


Figure 16: Sample air defense “Macro” operational concept

Figure 17 specifically selects one potential system option and presents its ability to meet the operational concept required by the customer.

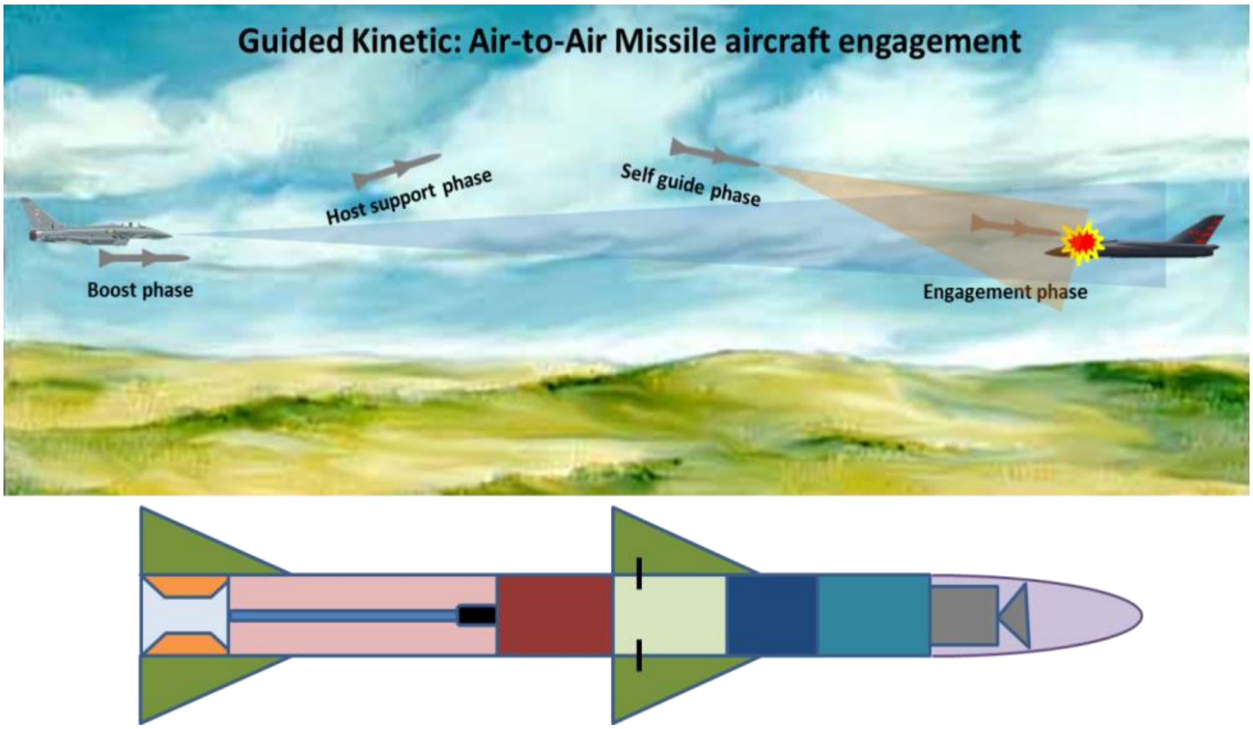


Figure 17: Sample air defense "Micro" operational concept

3.1.2 Requirements and constraints generation and tracing

The PM team performing the system design with STMI must have the initial set of requirements and constraints generated by the customer, approved by senior management and documented in a document like a CRD. Requirements are typically something to be obtained, while constraints provide boundaries or limits on the system for developing an acceptable system design. Sample constraints include maximum weight, dimensional limits, no hazardous materials, or cost limits. The aim should be to add as few constraints as possible, so as not to artificially restrict the search domain.

The following are guidelines for coordinating with the customer to create an executable CRD (adapted from Karl E. Wiegers' "Writing quality requirements"[257]). Each of the customer requirements must be:

1. Correct: Each requirement must accurately describe the functionality to be delivered. The reference for correctness is the source of the requirement, such as an actual customer or a higher-level system requirements specification. Only user representatives can determine the correctness of user requirements, which is why it is essential to include them, or their close surrogates, in inspections of the requirements. Requirements inspections that do not involve users can lead to developers saying, "That doesn't make sense. This is probably what they meant." This is also known as "guessing."
2. Feasible: It must be possible to implement each requirement within the known capabilities and limitations of the system and its environment. To avoid infeasible requirements, have a PM's SME work with the requirements analysts or marketing personnel throughout the elicitation process. This SME can provide a reality check on what can and cannot be done technically, and what can be done only at excessive cost or with other tradeoffs.
3. Necessary: Each requirement should document something the customers really need or something that is required for conformance to an external requirement, an external interface, or a standard. Another way to think of "necessary" is that each requirement originated from a source you recognize as having the authority to specify requirements. Trace each requirement back to its origin, such as a use case, system requirement, regulation, or some other voice-of-the-customer input. If you cannot identify the origin, perhaps the requirement is an example of "gold plating" and is not really necessary.
4. Prioritized: Assign an implementation priority to each requirement, feature, or constraint to indicate how essential it is to include it in a particular system design. Customers or their surrogates have the lion's share of the responsibility for establishing priorities. Adding lower priority constraints forms the basis for additional trade studies and design refinement.
5. Unambiguous: The reader of a requirement statement should be able to draw only one interpretation of it. Also, multiple readers of a requirement should arrive at the same interpretation. Natural language is highly prone to ambiguity, so

avoid subjective words like user-friendly, easy, simple, rapid, efficient, several, state-of-the-art, improved, maximize, and minimize. Words that are clear to the customer may not be clear to readers. Write each requirement in succinct, simple, straightforward language of the user domain, not in industry jargon. Effective ways to reveal ambiguity include formal inspections of the requirements specifications, writing test cases from requirements, and creating user scenarios that illustrate the expected behavior of a specific portion of the product.

6. Verifiable: See whether you can devise tests or use other verification approaches, such as inspection or demonstration, to determine whether each requirement is properly implemented in the system design. If a requirement is not verifiable, determining whether it was correctly implemented is a matter of opinion. Requirements that are not consistent, feasible, or unambiguous also are not verifiable.
7. Threshold Values: SMEs must only include the threshold values (minimal requirements that must be met) from the customer. A key attribute of the STMI VE process in stage-2 requires that the minimum (threshold) requirements be met to accurately define a system's "best value". Requirements above and beyond the minimums are considered "gold plating" and should be renegotiated with the customers.

The PM's team does not want to be stuck with unattainable requirements or constraints. Since the quality of any product depends on the quality of the raw materials fed into it, poor requirements cannot lead to excellent system design. On the other hand, having too many requirements can lead to contradictory conditions (achieving one requirement limits or fails another) and can generate an extremely limited design space. An overabundance of unnecessary requirements limits the PM team's trade space to explore the variety of system design options. Keeping only the necessary requirements in the initial design and potentially adding in secondary requirements during trade studies can be a good compromise to illustrate how a design evolves with each added requirement. Table 8 provides a summary of common system design requirements adapted from a traditional project design requirement guide[258].

Table 8: Common types of design requirements

General Types	Specific Design Requirements
Cost Target	• Cost to develop • Cost to purchase • Cost to use • Cost to maintain • Cost to repair • Cost to dispose
Physical Characteristics	• Weight • Density • Melting, boiling point • Color • Transparency • Reflectance • Surface texture (polished, rough) • Elasticity • Hardness • Ductility (ability to be drawn into a wire) • Magnetic properties • Electrical properties (resistance, impedance, etc.) • Impact resistance • Bending strength • Viscosity (the thickness and stickiness of a fluid) • Acoustics (pitch, sound transmission, resonance)
Aesthetics (how it looks)	• Style (art deco, Victorian, modern, medieval) • Color • Fit and finish (Is it built with care and attention to detail?)
Performance characteristics	• Accuracy • Strength • Reproducibility, repeatability (Does it always do the same thing given the same input?) • Speed • Acceleration • Deceleration, braking • Rolling resistance • Friction • Adhesion • Absorbency • Permeability (Do things leak through it?) • Resolution • Flammability (ability to set on fire) • Insulation value

Table 8: Common types of design requirements - continued

General Types	Specific Design Requirements
Geometry	• Size, overall dimensions • Curvature • Volume, capacity
Manufacturing considerations	• Difficulty of making • Equipment or manufacturing techniques required to build the invention (You don't want to build something from metal if all you have is a woodworking shop.) • Number of component parts • Labor requirements • Means of shipping or delivery
Environmental requirements	• Operating temperature range • Storage temperature range • Water resistance • Resistance to corrosion • Compatibility/interoperability with ____________ • Ability to withstand radiation (called radiation hardness)
Inputs/Outputs	• Energy/Fuel consumption • Labor • Product produced • Power • Pollution • Undesirable side effects ____________
Usability	• Ease of use • Ease of learning • Ease of repair/maintenance • Operator training • Service requirements • Reliability/Maintainability • Lifespan • Disposability
Regulatory & licensing considerations	• Meets government rules • Meets company or league rules (a sporting product) • Does it require paying a patent or license fee?
System specific	• Human factors • Specifically based on unique system

Once the requirements and constraints have been defined and documented, they become the basis for defining the key design requirements, system design models and constraints within which the system design must operate to meet its customer requirements.

3.1.3 Defining key parameters and system models

Every system design will have a primary set of requirements or Key Performance Parameters (KPPs) that must be achieved by the system design in order to be successfully accepted by the customer. Usually 2-4 performance characteristics are identified by the customer/user and are of critical importance (design power levels, weapon range, unit mass, etc.). Most of the system models that develop into objective functions used in the STMI stage two processes are based on meeting the KPPs. The KPPs are also the primary candidates for conducting single and multivariable sensitivity analysis in the STMI stage three processes.

System modeling describes the mathematical representation of the system component or overall system concept under consideration. It represents a solution method to evaluate input data based on meeting KPP criteria that is limited by the defined constraints. A common type of systems modeling is function modeling[259], with specific techniques such as the Functional Flow Block Diagram (FFBD). Once the basic system design has been established in the operational concept (like an Air-to-Air missile to engage combat aircraft at long range), these functional models can defined for each missile component and extended using functional flow blocking to link requirement models for further systems partitioning. Top level functional blocks can be rolled up sub-functions (levels) which are diagramed separately. Figure 18 provides an illustration of functional modeling and a functional flow block diagram for a single level of operations.

3.1.4 Technology database development

The technology database generation for STMI input is a vital precursor requirement for executing the STMI VE optimization process. Without correct (verified) data that is properly used (validated), any analysis, optimization or application will be rendered unreliable. In general, data verification and validation is used to evaluate whether data has been generated according to specifications, satisfy acceptance criteria, and are

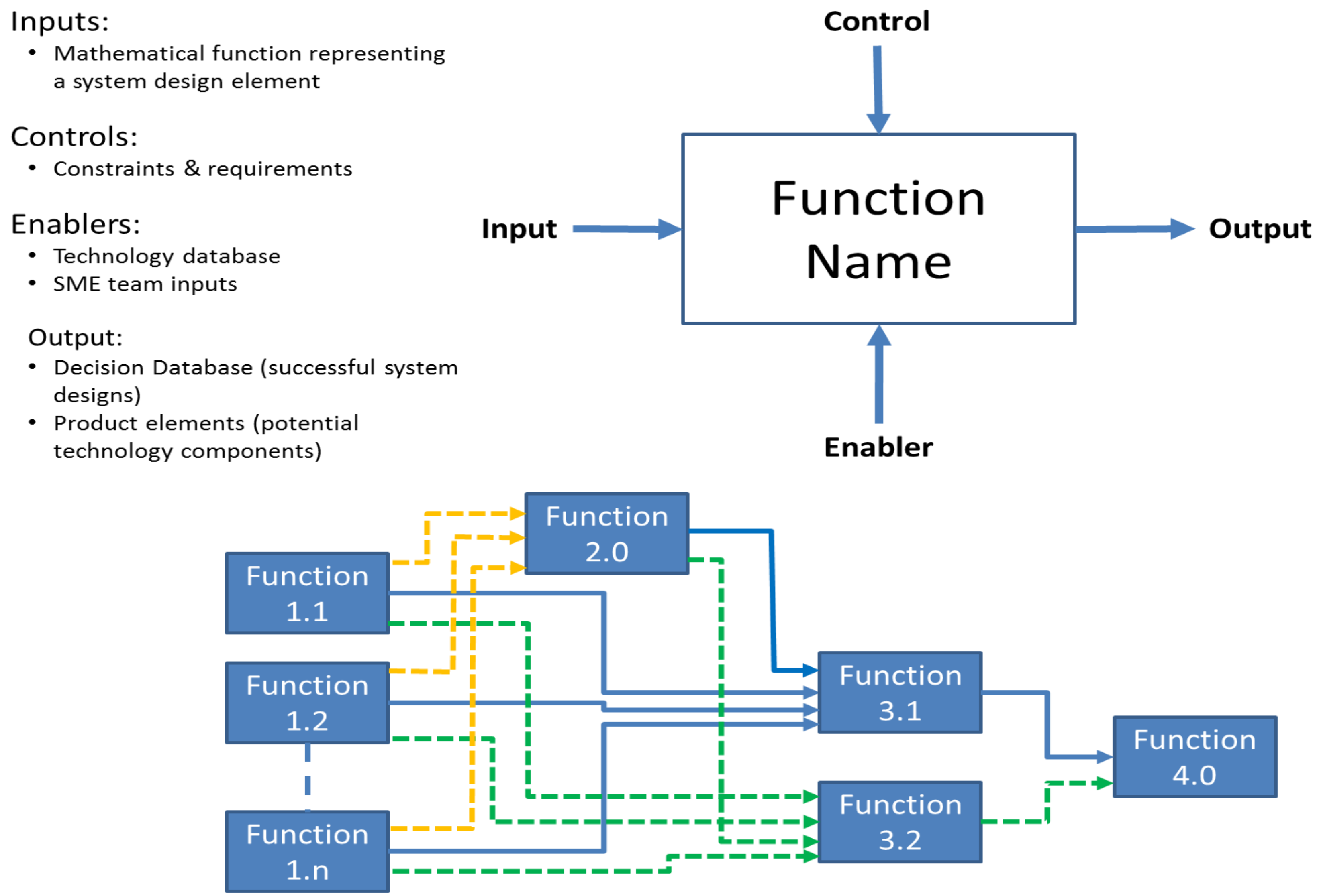


Figure 18: Sample of a functional flow block diagram, single level

appropriate and consistent with their intended use. Data verification is a systematic process for evaluating performance and compliance of a set of data when compared to a set of standards to ascertain its completeness, correctness, and consistency using the methods and criteria defined in the project documentation. Data validation follows the data verification process and uses information from the reference documentation to ascertain the usability of the data in light of its measurement quality objectives and to ensure that results obtained are scientifically defensible[260].

3.1.4.1 Database guidelines

SMEs on the PM team will typically generate the technology database. The following are guidelines for completing this task:

1. Technologies considered for the database must have achieved a level of maturity to offer a demonstrated capability. Industry and DoD program offices tend to start investing in technologies that are TRL-4, and integrating technologies that are TRL-6 or higher. Therefore the STMI database must consist of technology items that are TRL-4 (in development) to TRL-9 (fielded and commercially available). This gives the technology added to the STMI database at least a basic level of credibility and demonstrated proof-of-concept in a laboratory environment[261].
2. Each of the technology entries and their performance capabilities must be verified and validated with a supportable reference and applicability to the design based on the customer requirements. SMEs must make judgment calls when including or disregarding technologies for evaluation. Tying a decision to a CRD reference is the most defensible method (i.e. if the CRD has a “no environmentally hazardous materials” constraint, then radioactive components could be removed from evaluation).
3. The development schedule must include an estimated time to expend the development funds to bring the technology up to a TRL-6.
4. Lifecycle costs should include the following:
    a. Unit cost: per unit purchase price for a defined block of units (i.e. 10, 100, 1000, or 10000).

b. Development cost: the cost to mature the technology to at least a TRL-6 level for insertion into the system design. It could be zero if the technology is an exact fit for the system design.
c. Operations Cost: cost for users to operate the technology per year (i.e. power, training, and special consumable components).
d. Maintenance Cost: costs per year to keep an item in good condition and/or good working order. SME's should emphasize early and preventative maintenance in their cost estimates. Assuming no failures or costing out part failure leads to inaccurate and excessive maintenance budgets[262].
e. Disposal Cost: end of life costs of an individual unit for recycling, hauling away to the dump, any residual sale value, or hazardous material charges).

As an example, a database entry for "Technology1" might look something like this for use in the system analysis, including performance measures, development costs and schedule, and lifecycle cost:

<u>Technology1</u> (Name, mass (kg), power required (w), cost to develop to TRL-6 ($), schedule to develop to TRL-6 (months), unit cost ($), operational cost per year ($), maintenance cost per year($), disposal cost($))

or

<u>Technology1</u> (Propulsion igniter #1, 1.1, 120, 4738000, 18.9, 250, 120, 200, 2000)

3.1.4.2 Performance data

Typically, key performance parameters of the technology are identified during the requirements engineering stage and are included as factors in the database (e.g.. material properties of density, strength and unit cost). When the SMEs are preparing the technology database, technology performance factors need to be referenced and applicable to the system being designed.

3.1.4.3 Cost and schedule estimation

Estimates of cost and time required achieving the systematic steps to a TRL-6 ranking and documenting lifecycle costs are a central pivot point for the STMI database and successful STMI process execution. All the cost estimates must also be verified and validated for use in the planned system design. Optimistic or biased estimates vs. ones linked to historical and engineering estimates can significantly skew the results of the optimized technology mix. The World Wide Web provides an enormous wealth of time and cost estimation guides based on technology or market areas from reputable government agencies and peer-reviewed periodicals (e.g. energy[263], construction[264], and nuclear power[265]). DOE G 430.1-1 (1997)[266] and Ereev & Patel (2012)[267] provide some additional guidelines for estimating specialty costs like R&D maturation and production. Additional “rules-of-thumb” can be applied to help balance the engineering estimate to account for the “unknown-unknowns” (many government offices use % “safety factors” against the engineering estimates that are based on the TRL level and SME experience).

3.1.4.4 Cost and schedule uncertainty model

SME estimates for technology costs and schedules are subjective and can be considered to be operating under uncertainty, holding the largest risk to the integrity of the technology database. In order to do better than a SME WAG (Wild Approximate Guess), the estimates can be further enhanced by incorporating a certain amount of statistical decision making which allows the decision maker to factor in acceptable risk levels and/or probability. If probabilities can be assigned, SMEs can now operate in a “decision making under risk” environment, where risk can be viewed as outcomes with attached probabilities. The probabilities are often estimated or defined from experimental data or historical data[268]. The best choice strategy becomes identifying the action with the best “Expected Value” (E_i) which is the summation of the reward (r_{ij}) times the probability of occurrence (p_j) of the reward for each state (s_j). The expected value with probability analysis is also known as a “realistic” risk decision view and is illustrated in Equation 7.

Equation 7: $$E_i = \sum_{j=1}^{N} r_{i,j} \cdot p_j$$

Expected values do not always accurately reflect choices made in practice; and this is particularly true when losses or gains involved are large, compared with the resources available[269]. There are problems associated with just going with the "results" of the decision making tools, given the reward (outcome) of either under-running or over-running your budget action. Selecting an action that yields a higher expected value means a reduced risk of failure, but a higher initial capital investment (which may be harder to secure). In the government acquisition community, having a higher expected value indicates you did not spend your entire budget, and that can mean money being removed from your program or a reduced budget in the future. Having a high or low expected value also indicates poor budget planning and resource management by the decision maker. The example presented in Table 9 illustrates the expected value calculations where a budgeted "action" is planned to develop a technology over a scheduled time period, with probabilities of completion assigned for each period option.

Table 9: Example decision making under risk (sample probabilities assigned)

Initial budget action, a_i ($K)	**Schedule, s_1 (months), Reward, r_{ij} ($K), Probability, P_i**							**Expected Value**
	12	16	20	24	28	32	36	
	0.005	0.03	0.1	0.45	0.3	0.1	0.015	
4000.0	600	-200	-1000	-1800	-2600	-3400	-4200	-2084
5000.0	1600	800	0	-800	-1600	-2400	-3200	-1084
5500.0	2100	1300	500	-300	-1100	-1900	-2700	-584
5750.0	2350	1550	750	-50	-850	-1650	-2450	-334
6084.0	2684	1884	1084	284	-516	-1316	-2116	0
6250.0	2850	2050	1250	450	-350	-1150	-1950	166
6500.0	3100	2300	1500	700	-100	-900	-1700	416
7000.0	3600	2800	2000	1200	400	-400	-1200	916
8000.0	4600	3800	3000	2200	1400	600	-200	1916

Start-up fixed cost ($K) = 1000

Variable cost per month ($K) = 200

Recommended budget action: $6,084,000

Recommended composite schedule: 12[0.05]+16[0.03]+20[0.1]+24[0.45]+28[0.3]+32[0.1]+36[0.015] =

25.5 months

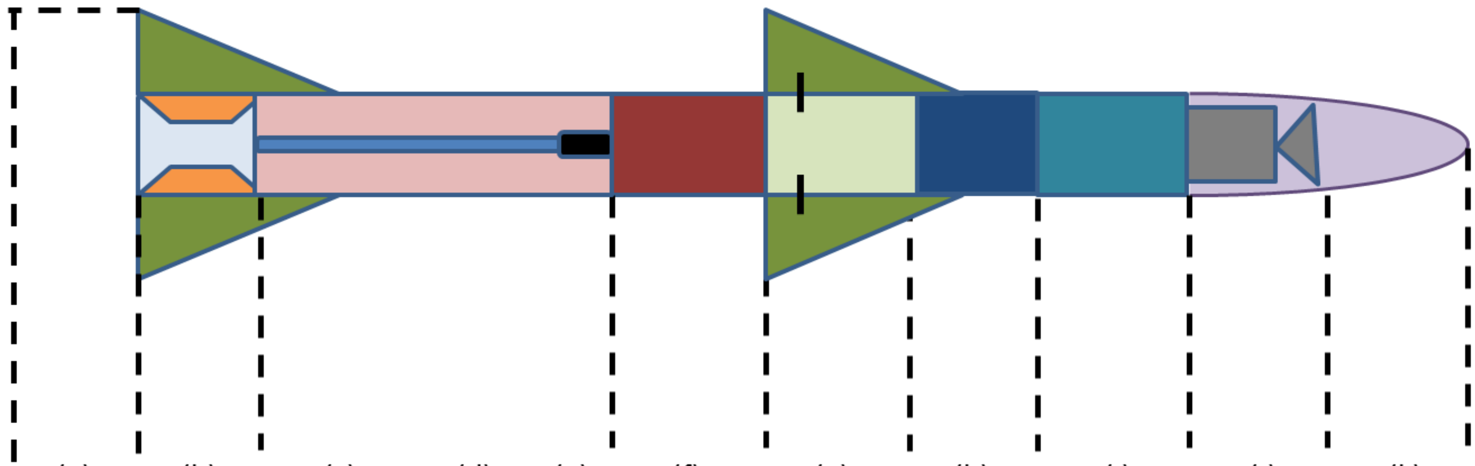
The rewards (outcomes) are based on coming in over or under budget due to fixed and monthly variable costs of the technology development project. A recommendation for the SME (and use within the STMI database building process) would be to find the action (initial budget) that would yield an expected value as close to zero as possible, thus balancing the possibilities for a realistic budget to build a threshold technical capability coming in on the expected schedule. This is in effect applying a personal user utility ($U_{i,j}$) to the results, forcing the expected value equation to zero[270] as illustrated in Equation 8.

Equation 8: $$E_i = \sum_{j=1}^{N} U_{i,j} \cdot r_{i,j} \cdot p_j = 0$$

Operationally, iteration with a spreadsheet EV payout matrix (as illustrated in Table 9) can also meet the $E_i \approx 0$. When applied to the STMI database, the SME meta-tags the interested technology with the threshold performance capability, the budget (action) that forces the EV equation to zero, and the composite schedule ID defined by summing the products of the probabilities and schedule states.

3.2 <u>Stage two: STMI core process</u>

Like the classic problem faced by someone who is constrained by a fixed-size knapsack and must fill it with the most valuable items, STMI exercises the same practice, evaluating the best technologies for a system design. STMI stage two executes this technology evaluation process through three basic steps. Step one functions evaluate technology components from the STMI technology database for potential inclusion into a system design based on meeting a fixed set of customer requirements and constraints. These system components are then evaluated for interactions between the selected technology options and establish a successful system design. Step two takes all of the successful systems designs and ranks them by best value (BV), yielding the overall best BV system design. Step three takes the BV system design and lays out the individual technologies as a STP development schedule input, noting costs and time required to develop the technology mix. To illustrate this process, a sample system of an Air-to-Air Missile (AAM) designed to engage combat aircraft as described in the operation concept graphic in Figure 17 will be used and is presented in Figure 19.



System component	(a) Structure	(b) Nozzle	(c) Propellant	(d) Grain	(e) Igniter	(f) Warhead	(g) Control	(h) Power	(i) Guidance	(j) Seeker	(k) Nose cone
Technology options	8	6	10	4	3	8	4	6	7	5	3

Potential technology combinations: 8x6x10x4x3x8x4x6x7x5x3= 185,241,600

Figure 19: Sample AAM system design

This AAM example is not a complete system design, but is used to demonstrate the STMI stage-2 processes and the potential complexity of evaluating over 185 million potential system designs.

3.2.1 System design objective function operations (step-1)

To execute STMI stage-2, step-1, the system design component objective functions are applied from the STMI stage-1 system models developed by the SMEs. These objective functions are usually a deterministic set of design equations that form the basis to evaluate candidate technologies for each system component in a potential system design. They are the first "test" of a technology combination to see if they meet threshold customer requirements, which include the KPPs. For our AAM example, the first set of component objective functions are illustrated in Figure 20 and are designated 1.x. They evaluate the step-1 system design and technology matrix which is designated in matrix Equation 9 with the technology increments indicated by a-k.

Equation 9: AAM System Design (a, b, c, d, e, f, g, h, I, j, k)

Once successful components in the potential system design have been evaluated against the customer requirements/constraints, the interactions with other technology components are evaluated. Many of the technologies have interactive input to the system design (i.e. geometry, mass, power, temperature) and depending on the technology combination chosen, they can end up being ruled out due to system design constraints. Returning to our AAM example, the interactions include component power, mass and length contributions and are designated as 2.x, 3.x, 4.x and 5.x functional blocks. Each of the interaction functional blocks are still bound by the customer requirements and constraints, and access their appropriate section of the technology database for that particular evaluation increment.

A failed component design fails the entire system design combination and the failed system design is removed from further evaluation. Successful system designs meeting the customer threshold requirements with solution sets of technologies are then passed along to the STMI stage-2 process to be ranked by the VE best value process.

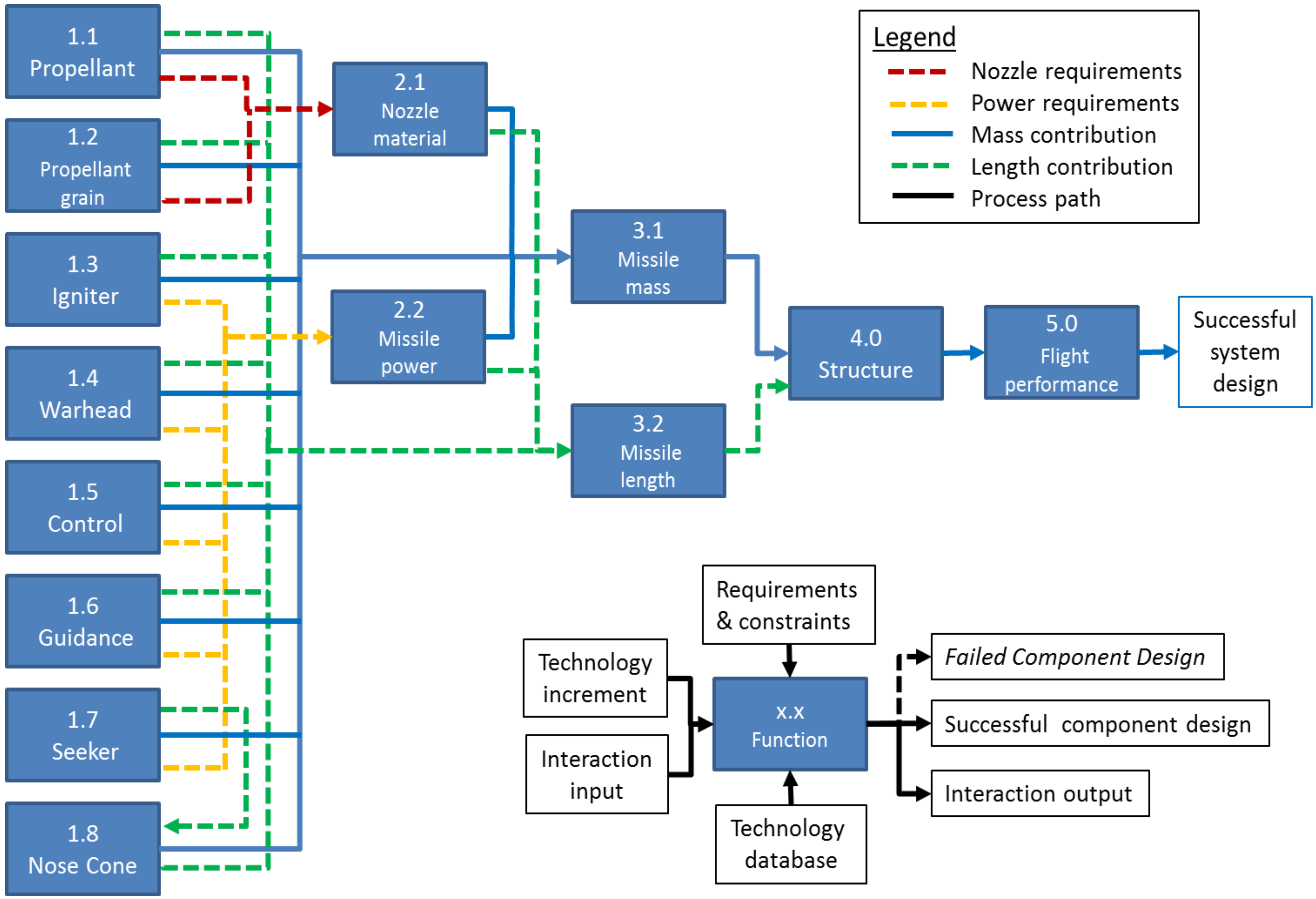


Figure 20: STMI system design Function Flow Block Diagram for AAM example

3.2.2 *Incorporating Value Engineering "best value" (step-2),*

To execute STMI stage-2, step-2, the Value Engineering (VE) best value (BV) process becomes the primary determiner for the final system design. VE focuses on selecting the best successful system design from step-1 based on its overall lifecycle costs, from development through disposal. For each successful system design, the technology metadata tags are indicated by the design matrix noted in Equation 9. These technology metadata tags allow the STMI VE process to collect the cost data for each successful system design.

STMI VE uses the cost metadata to calculate a local "worth" value for each successful system design based on the technology solution set maturation cost to a Technology Readiness Level six (TRL-6) for system incorporation and unit cost. The lowest "worth" value of all of the successful system designs becomes the global system design worth or "minworth". This "minworth" indicates the lowest cost to develop and purchase a system that meets the minimal (threshold) customer requirements.

STMI VE continues to use the cost metadata to calculate a local lifecycle "cost" value for each successful system design based on the customer specified design life of the system. This system "cost" value is based on the technology solution set's combined development maturation, unit, operational, maintenance, and disposal costs. This gives the specific system design a truer indication of the total costs over its expected lifespan.

Finally, STMI VE utilizes the global "minworth" divided by the local system design "cost" to generate a system BV which optimizes the costs associated with meeting the customer's threshold system requirements. The technology set within the system design that yields the highest BV is considered the optimum system and get its costs and schedule requirements pulled from the technology database metadata and presented as STMI stage-2, step-3 input data for the overall system design Strategic Technology Plan.

Figure 21 illustrates the STMI VE process for determining a BV for the AAM example for a representative 20 year operational lifetime with a purchase of 500 units. A successful system design's individual worth ($Worth_{System}$) are determined for this example with the number of units purchased (unit buy) in Equation 10. The overall minimum worth ($Worth_{min}$) of the successful system designs is selected as the smallest $Worth_{System}$ of all successful system designs. Successful system lifecycle costs ($Cost_{Lc}$) are determined for this example with yearly operations and maintenance costs in Equation 11. Individual system "best values" are calculated with Equation 12. The overall "best value" system has the highest "Best value" score and contains the recommended technology solution set for system development

Equation 10: $Worth_{System} = Cost_{Maturation} + Cost_{Unit} * (unit\ buy)$

Equation 11: $$\begin{aligned} Cost_{Lc} = {} & Cost_{Maturation} + Cost_{Unit} * (unit\ buy) \\ & + Cost_{Operations} * (unit\ buy) * (operational\ lifetime) \\ & + Cost_{Maintenance} * (unit\ buy) * (operational\ lifetime) \\ & + Cost_{Disposal} * (unit\ buy) \end{aligned}$$

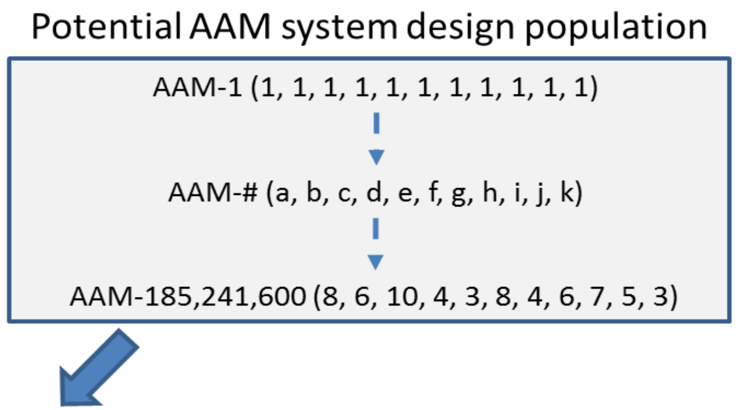
Equation 12: $\text{Best Value}_{System} = \frac{Worth_{min}}{Cost_{Lc}}$

Trade studies in STMI stage-3 can focus on system designs with constrained developmental budges, which can yield different BV solutions (see note in Figure 21).

3.2.3 Strategic Technology Plan input (step-3)

STMI stage-2, step-3 takes the best value optimized system design and extracts the technology solution set developmental schedule and cost metadata. This metadata provides a listing of the best technologies, their required development schedule to attain a TR-6 maturity and the estimated cost to achieve that maturity level.

For the AAM example, the BV optimized system from Figure 21 is designated system design AAM-11,069,111 and is laid out for STP input in Figure 22. Its correlating technology dataset would be taken from the technology set matrix noted in Equation 9.



STMI Stage-2, Step-1

Successful AAM designs w/ cost metatags ($K)

Successful system design designator	Costs ($K) maturation	unit	operational	maintenance	disposal
AAM-5	21000	150	16	11	35
AAM-243	25000	155	15	11	22
AAM-3,101	58000	145	12	9	27
AAM-78,124	35000	175	15	10	26
AAM-11,069,111	110000	105	10	7	20
AAM-68,452,120	55000	115	13	9	23
AAM-89,231,001	46000	125	15	8	25
AAM-101,425,273	18500	127	16	15	21
AAM-178,542,100	195000	90	8	4	15
AAM-178,542,104	22000	125	16	11	20

values are for example only and are not representative of any specific AAM system

one time technology maturation cost

operational and maintenance cost are yearly per unit

one time disposal cost per unit

STMI Stage-2, Step-2

Successful AAM designs best value, 20 year life

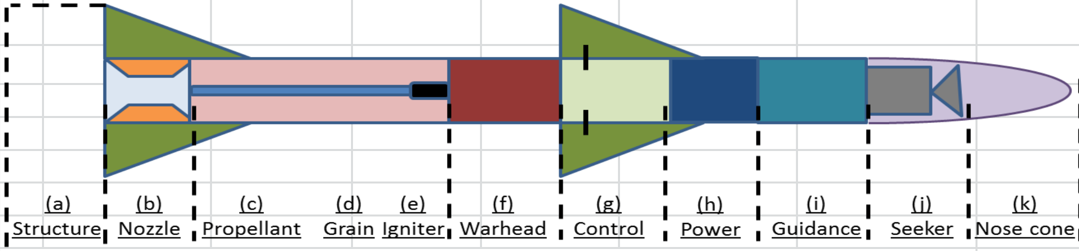
Successful system design designator	500 units @ ($K) worth	lifecycle cost	BV score
AAM-5	96000	383500	0.2138
AAM-243	102500	373500	0.2195
AAM-3,101	130500	354000	0.2316
AAM-78,124	122500	385500	0.2127
AAM-11,069,111	162500	342500	0.2394
AAM-68,452,120	112500	344000	0.2384
AAM-89,231,001	108500	351000	0.2336
AAM-101,425,273	82000	402500	0.2037
AAM-178,542,100	240000	367500	0.2231
AAM-178,542,104	84500	364500	0.2250

Minworth of systems

"best value" of systems

potential alternative "best value" if developmental budget is constrained

Figure 21: STMI VE process operation for “best value” selection



STMI BV optimized Sample AAM system design (2, 3, 7, 1, 2, 4, 2, 6, 5, 5, 1)

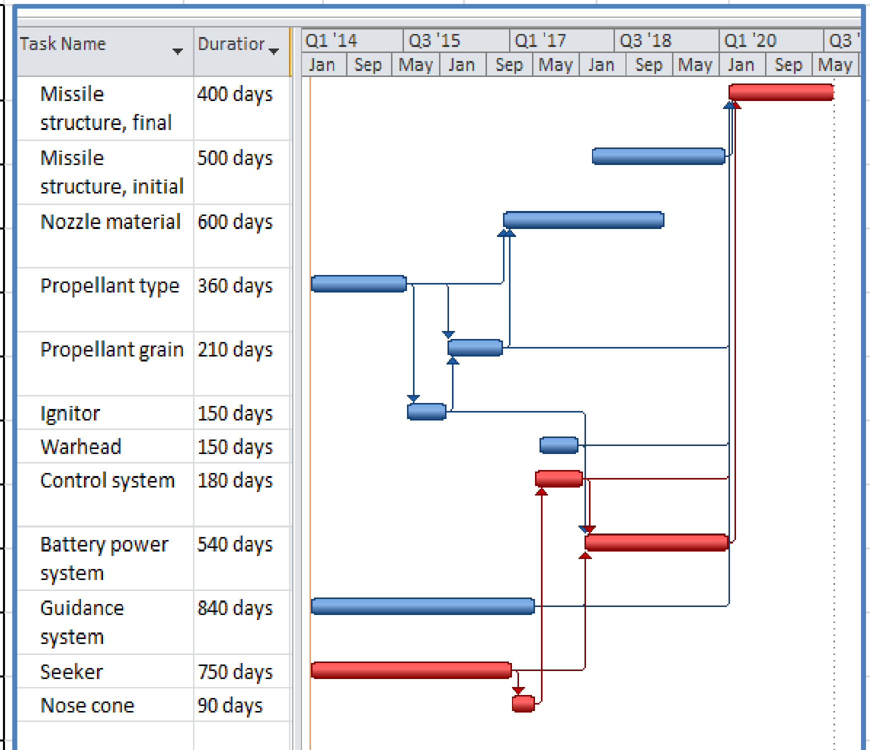
Strategic Technology Plan

PM team proposed AAM system design

Schedule time line: FY14-FY21

FY budgets	($M)	FY budgets	($M)
FY14	16.6	FY18	16.6
FY15	16.6	FY19	16.6
FY16	16.6	FY20	6.4
FY17	16.6	FY21	4

	Technology component	Technology selection	Maturation cost ($K)	Maturation schedule (months)	Dependancies
1)	Missile structural	2	28000	30	4, 6, 7, 9, 11
2)	Nozzle material	3	15000	20	3, 4
3)	Propellant type	7	4400	12	none
4)	Propellant grain	1	4500	7	3, 5
5)	Ignitor	2	2500	5	3
6)	Warhead	4	3500	5	none
7)	Control system	2	5000	6	none
8)	Battery power system	6	12000	18	5, 6, 7, 9, 10
9)	Guidance system	5	19500	28	none
10)	Seeker	5	15000	25	none
11)	Nose cone	1	600	3	10
		total	110000		



Red indicates critical path schedule

Figure 22: STMI BV system design metadata applied to STP schedule & budget

With the matrix notation, the correct technology database entries would be accessed and provided for inclusion for the STP with a project planning software such as Microsoft Project[271]. The PM's team would use the STMI optimized technology data set to plan out the technology maturation schedule, noting where technology development could be overlapped (completed in parallel) given adequate budgetary support. Using the Functional Flow Block Diagram in Figure 20, dependencies of the technology interactions can be taken and modeled within the STP schedule input. Long lead items (technology requiring more maturation time) would be identified and accommodated within the STP. The completed STP would incorporate all of the technology component schedules and a proposed master yearly budget that can be prepared for the system design development. This master yearly budget would be based on the maturation cost for each technology, technology developmental dependencies, and where their maturation schedule was placed on the STP.

3.2.4 Optimization process

To smoothly transition between STMI stage-2 steps, an evaluation methodology must be incorporated to examine the "population" of potential system designs. Two overarching optimization methods are presented to allow STMI stage-2 to evaluate the pool of potential technology combinations through its three step process. The first method is a looping algorithm designed to be an "all options" analysis, which guarantees finding the optimum BV design, but at a cost of time and computer processing power. The second method is a modern genetic algorithm (GA) metaheuristic analysis which can greatly reduce the analysis time at the cost of potentially generating just a "near" optimum BV solution.

3.2.4.1 All options optimization

The all-options optimization for STMI is set-up to evaluate all of the technology options for each system component and track the highest BV score.

The basic framework for the STMI all options algorithm is laid out next.

```
Technology matrix D(t)[a,b,c,d,e,f,g,h,….] (pulled from database)
t =0; t'=0; BestBV=0; BestSDt=0
minworth = 1
WHILE technology evaluation loops [a,b,c,d,e,f,g,h,….] are not complete DO
  Evaluate system component designs D(t) against objective functions
  IF D(t) is a successful design THEN
      Establish system Worth(t) and Cost(t) score from technology matrix
      IF Worth(t) < minworth THEN minworth =Worth(t)
      BV(t)=minworth/Cost(t)
  ELSE BV(t) = 0; Worth(t)=0; Cost(t)=0
  ENDIF,  t = t+1
ENDWHILE
WHILE t'<t DO    (Best Value calculation for successful system designs)
  IF BV(t') > 0 THEN
      BV(t') = minworth/cost(t')
      IF BestBV>BV(t') THEN
            BestBV = BV(t')
            BestSDVt = t'
      ENDIF
  ENDIF,  t'=t'+1
ENDWHILE
Return best BV solution found + best system design BestSDt
```

The first loop set becomes a series of nested DO-LOOPs, one for each technology component. Within these loops, the system components for each potential system design are evaluated against the threshold customer requirements, and interactions between components are addressed. Successful system designs are then tagged with their VE cost and worth values. The global minworth is tracked and an initial BV calculation is determined based on the current minworth. Unsuccessful system designs are removed from the BV calculations.

The second loop takes the final global minworth value and updates each successful system design with its final BV calculation. The best BV system design is tracked and provided as a final output. At the end of the optimization run, the best BV score is used for the step-3 final technology recommendation and maturation schedule for the system design. While this method is guaranteed to find the “optimum” BV score, it is computationally intensive and can take long periods of time to complete the analysis for systems with large technology component databases and complex interactions.

3.2.4.2 Metaheuristic search optimization

Since the majority of the computational power required for the optimization occurs during the object function evaluation, if solutions could be evaluated without every single technology option explored, a significant computational time savings can be realized. Metaheuristics offer a means to balance computational efficiency while retaining acceptable accuracy. Given the non-continuous nature of the technology “population” being evaluated, a population based Genetic Algorithm (GA) metaheuristic was developed to speed-up the STMI stage-2, step-2 optimization process.

The reduction of system computational requirements is illustrated in Figure 23 when comparing “all-options” optimization and the GA optimization.

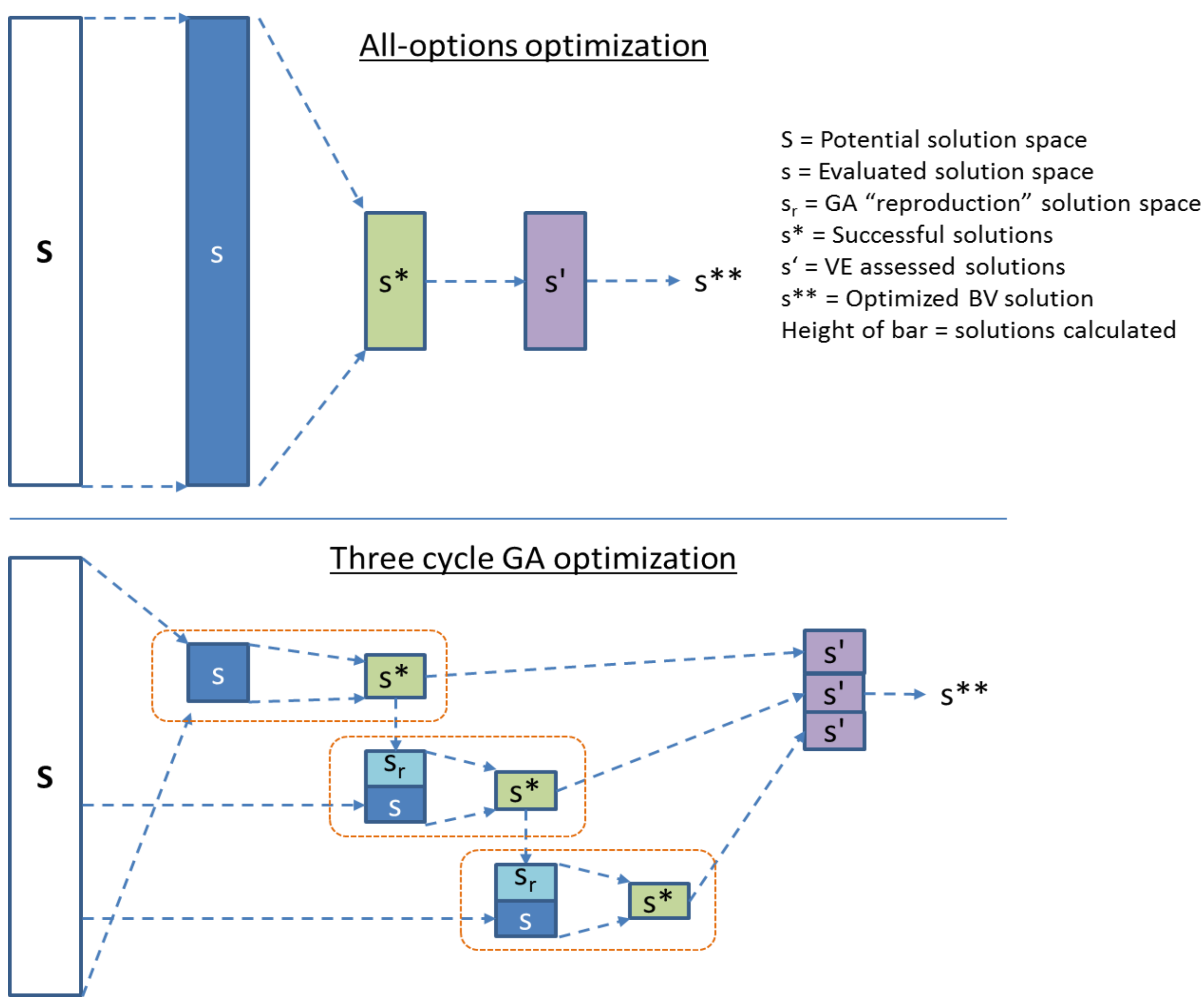


Figure 23: Computational requirements illustration between optimizers

This GA offers several advantages over traditional parameter optimization techniques. Given the non-differentiable or otherwise ill-behaved (non-continuous) problem associated with the STMI technology analysis, many traditional optimization techniques are of no use or tend to converge to a local optimum once they are in its vicinity. Since the GA does not require gradient information, it can be used to search highly nonlinear spaces for global optima. GAs conduct search from many random points simultaneously, and are therefore more likely to find a global optimum, especially when examining real-world, multi-objective optimization where meeting various requirements are specified[272].

The framework for the STMI GA algorithm is laid out next.

```
Generate initial random population P(0) with s samples
  Hash table generation/check
Termination condition (set by user)
t =0
minworth = 1
BVdesign = 0
WHILE termination conditions not met DO
  Evaluate new P(t) population against objective functions
  Execute VE operations
     Calculate Cost(t) and Worth(t) for new surviving s* sample of P(t)
     IF Worth(s*) < minworth THEN minworth =Worth(s*)
     Establish BVscores(s*) for all surviving s* sample of P(t)
        IF BVscore(s*) > BVdesign THEN BVdesign2 = BVscore(s*)
  Execute genetic operators
     P'(t) = Select s*/2 of the best (P(t)) based on BV scores
     P''(t) = Apply Reproduction Operators(P'(t)) to fill (s-s*)/2 population samples
     Hash table check
     P(t+1) = P(t) + P''(t) + new random population fill based on (s-s*)/2 samples
               (brings population back up to s samples)
     Hash table check
  Check termination condition
     IF (BVdesign – BVdesign2) < termination condition
     THEN termination condition met
     ELSE BVdesign = BVdesign2
  t = t+1
ENDWHILE
Return best solution found
```

To initiate the GA algorithm, STMI first generates an initial random population out of the total system design population pool. The number of samples “s” is user selectable and finding the best starting value is traditionally difficult[273] and system dependent. GA experts recommend having at least 50 to 500 random samples of the total population pool to get an initial starting population[274], depending on the number of factors being addressed (more factors, higher sample number). The algorithm also checks each generated member against a “hash table” which tracks all designs placed in the “s” sample group. When a new potential design is to be added to the sample population (either randomly or through the reproduction operators), the algorithm checks the hash table for any duplicates. If the new potential design is a duplicate, it is thrown out and the design operator is repeated until a new design is generated that is unique to the “s” sample pool.

The GA algorithm starts and ends with a set sample population pool “s” placing it in the “steady state” population style of GA designs. This is beneficial from the standpoint of creating a reduced memory load, but runs the risk of prematurely converging to a few highly fit individuals[275]. The other advantage of the SMTI GA algorithm is that the number of fittest “parents” in P’(t) and consequently “children” in P’’(t) are variable, based on number of system designs surviving the objective function fitness criteria. To minimize premature convergence, the GA algorithm injects additional random population picks at the P(t+1) stage to diversify the population through the next fitness assessment with the objective functions.

Within the STMI VE algorithm, the objective functions for each system component are the first survival “fitness” tests for each system design population member. Unsuccessful designs “die” and are removed from the population list, (s). “Survivors” or successful system designs population (s*) flow into the VE best value analysis. The successful system designs within the top 50% of the BV scores are chosen to “procreate” with the genetic operators. New system design “children” are generated and replace half of the “dead” (s) population. An additional round of random population generation fills in the second half of the “dead” (s) population. This cycle repeats until the best BV score only changes by a user selected amount.

3.2.4.3 Optimization for STMI

For this research, a Microsoft Excel spreadsheet was selected demonstrate the STMI "all case" algorithm operations. The main advantage of this approach was twofold. First, that the spreadsheet analysis provides an excellent "visual" of the operations and the specific factors that most impact the overall system design. Second, the initial implementation guaranteed an optimum result for the system design solution space, demonstrating the applicability of the STMI process. The limitation of this approach was that the spreadsheet tends to be resource limited to a smaller system population sets.

3.2.5 Micro and Macro STMI operation

The STMI process also allows a PM to conduct apples-to-apples comparisons of BV for macro-level system designs (i.e. a final system selection for production) while optimizing micro-level systems (i.e., demonstration prototypes vying for a development decision). For example, let's expand out the illustration in Figure 24.

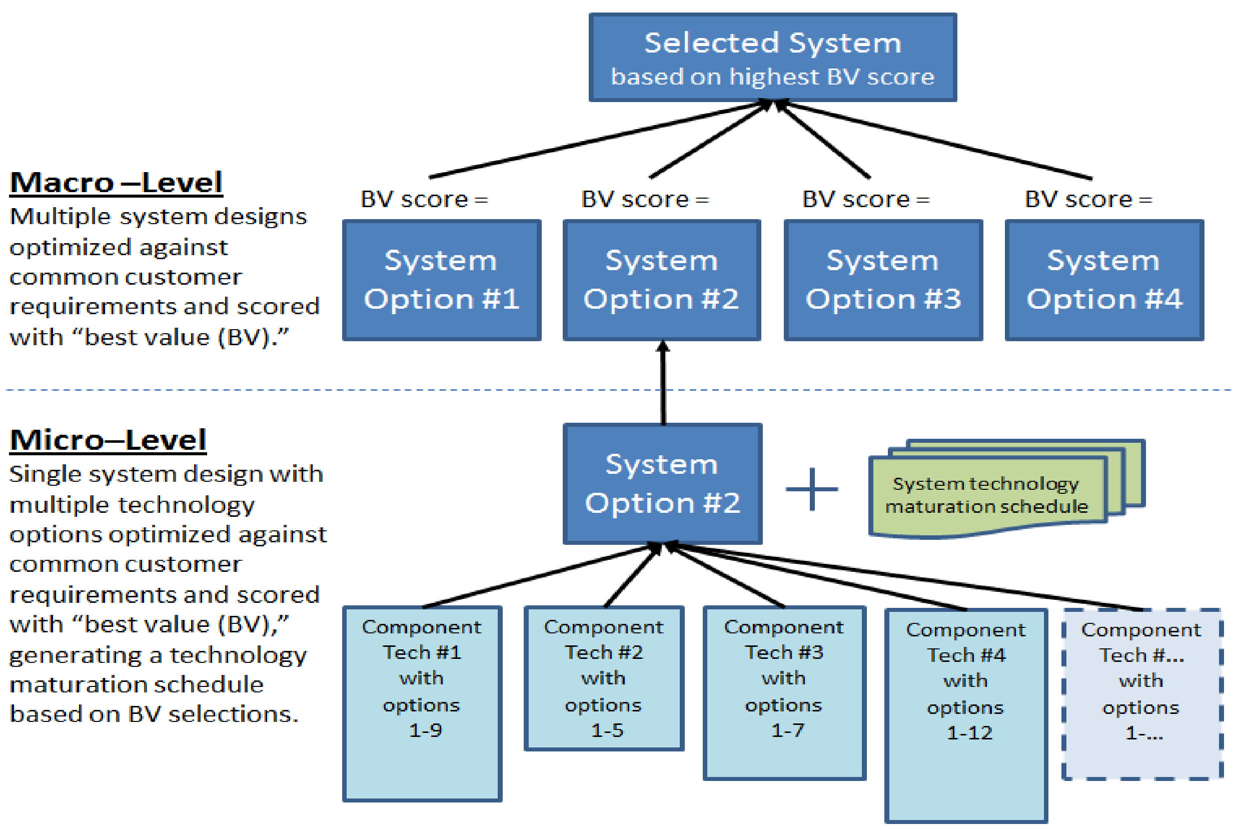


Figure 24: STMI macro-micro system optimization process

STMI offers a micro-level BV design for one macro-level system design proposal that meets the primary customer requirements. The PM has had all the macro-level systems optimized in a similar manner. Since the “worth” basis for each system was defined at the micro-level, it is carried up and compared at the macro-level with its peers. The lowest macro-level “worth” is selected as the overall macro worth and a new BV score is generated for each of the designs based on the overall macro worth divided by the individual macro-level lifecycle cost. The recommended overall design has the highest BV score and its corresponding technology database entry provides the specific technologies to develop by the PM team.

3.3 Stage 3: Post-process analysis

3.3.1 Trade-off study analysis

Once the initial STMI plan is generated, additional “what if” trade study scenarios can be rapidly performed to:

- Examine additional alternative technologies early in a program concept (add new technologies to the database for consideration)
- Analyze available trade-space within the design (change the requirements)
- Show impacts to system cost and schedule if component technology timelines and/or costs are constrained (limited development budget, or limited schedule availability)

3.3.2 Sensitivity analysis

To address PM’s concerns with data uncertainty and propagation through the STMI objective functions, two types of sensitivity analysis are recommended. The first type is a One-Variable-at-a-Time (OVAT) sensitivity analysis, where a single key factor is varied and results examined. The second type is a Design of Experiments (DoE) approach that allows multiple key factors to be purposefully varied together and then accurately predict how the inputs and their interactions affect the outputs.

For the AAM system design example, primarily cost data will be the variables of choice to examine. The system’s technology performance levels are held constant while the cost associated with developing them are allowed to vary in the maturation costs. Further sensitivity analysis runs could also be performed in a similar manner by changing the technology performance levels and examining the design changes in the BV results.

3.3.2.1 OVAT approach

A common approach to executing the OVAT for a sensitivity analysis is to identify the critical input variables (performance, schedule and cost) for the top BV system design technology mixes, and vary them upon an optimistic (best case) value, most likely (expected or baseline) value, and pessimistic (worst case)[276].

The resulting BV scores are then recorded and compared. The range of the BV scores, indicated in Equation 13, gives an indication of risk level (larger the range, higher the risk due to changes in the input variable) and an example is illustrated in Table 10 where the lowest range values are noted in blue highlight.

Equation 13: OVAT BV Range = (BV "best cost" score) – (BV "worst cost" score)

Upon review of the Table 10 OVAT sensitivity analysis, the PM's team would then offer the best designs (ones with lowest ranges of BV change for a given high/low input set) for each of the critical input variables. A PM concerned with cost changes due to a potentially longer system operational lifetime might select the technology set within the AAM-11,069,111 design which shows a lower BV range (risk indicator) compared to all of its competing designs. A PM primarily concerned with operational lifecycle costs impacts would also have a clear winner with the AAM-11,069,111 design due to four of the five cost BV ranges (risks indicators) being lowest. If near term fiscal realities where the driving force, either in defending the budget for the number of units bought or defending the research and development funding to mature the new system's technologies, the AAM-101,425,273 or AAM-3,101 system designs might be less risky options to explore.

Table 10: Example of OVAT sensitivity analysis with AAM system design

	Sensitivity Analysis OVAT (BV Score)															
	Maturation Cost				Operations Cost				Maintenance Cost				Disposal Cost			
AAM Successful System Design	Best (-10%)	Base	Worst (+20%)	Range	Best (-10%)	Base	Worst (+20%)	Range	Best (-10%)	Base	Worst (+20%)	Range	Best (-10%)	Base	Worst (+20%)	Range
AAM-5	0.215	0.2138	0.2115	0.0035	0.2231	0.2138	0.1974	0.0258	0.2201	0.2138	0.2022	0.0179	0.2148	0.2138	0.2119	0.0029
AAM-243	0.221	0.2195	0.2166	0.0044	0.2287	0.2195	0.2032	0.0255	0.2262	0.2195	0.2073	0.0189	0.2202	0.2195	0.2183	0.0019
AAM-3,101	0.2355	0.2316	0.2243	0.0112	0.2398	0.2316	0.2169	0.0228	0.2377	0.2316	0.2204	0.0173	0.2325	0.2316	0.2299	0.0026
AAM-78,124	0.2147	0.2127	0.2089	0.0057	0.2213	0.2127	0.1974	0.024	0.2184	0.2127	0.2022	0.0162	0.2134	0.2127	0.2113	0.0021
AAM-11,069,111	0.2474	0.2394	0.225	0.0224	0.2466	0.2394	0.2262	0.0204	0.2444	0.2394	0.23	0.0144	0.2401	0.2394	0.238	0.0021
AAM-68,452,120	0.2422	0.2384	0.231	0.0113	0.2477	0.2384	0.2216	0.0261	0.2448	0.2384	0.2265	0.0183	0.2392	0.2384	0.2368	0.0024
AAM-89,231,001	0.2367	0.2336	0.2277	0.0091	0.244	0.2336	0.2152	0.0288	0.2391	0.2336	0.2234	0.0156	0.2345	0.2336	0.232	0.0025
AAM-101,425,273	0.2047	0.2037	0.2019	0.0028	0.2122	0.2037	0.1887	0.0234	0.2116	0.2037	0.1896	0.022	0.2043	0.2037	0.2027	0.0016
AAM-178,542,100	0.2356	0.2231	0.2017	0.0339	0.2281	0.2231	0.2138	0.0143	0.2256	0.2231	0.2184	0.0072	0.2236	0.2231	0.2222	0.0014
AAM-178,542,104	0.2263	0.225	0.2223	0.004	0.2353	0.225	0.2068	0.0285	0.232	0.225	0.2122	0.0198	0.2256	0.225	0.2237	0.0018

	Sensitivity Analysis OVAT (BV Score)											
	Operational Life of System				Number of Units Purchased				Unit Cost Variance			
AAM Successful System Design	Best (30yrs)	Base (20yrs)	Worst (15yrs)	Range	Best (1000)	Base (500)	Worst (250)	Range	Best (-10%)	Base	Worst (+20%)	Range
AAM-5	0.1581	0.2138	0.2595	0.1013	0.195	0.2138	0.2485	0.0534	0.2181	0.2138	0.2058	0.0123
AAM-243	0.1629	0.2195	0.2658	0.1029	0.2015	0.2195	0.2522	0.0507	0.2242	0.2195	0.2108	0.0134
AAM-3,101	0.1786	0.2316	0.272	0.0933	0.2238	0.2316	0.2439	0.0201	0.2365	0.2316	0.2225	0.014
AAM-78,124	0.1606	0.2127	0.2539	0.0932	0.1977	0.2127	0.239	0.0413	0.2177	0.2127	0.2035	0.0142
AAM-11,069,111	0.1918	0.2394	0.2733	0.0815	0.253	0.2394	0.2221	0.0309	0.2431	0.2394	0.2323	0.0108
AAM-68,452,120	0.1806	0.2384	0.2837	0.1031	0.2299	0.2384	0.2519	0.022	0.2424	0.2384	0.2307	0.0118
AAM-89,231,001	0.176	0.2336	0.2794	0.1034	0.2218	0.2336	0.2531	0.0313	0.2379	0.2336	0.2256	0.0123
AAM-101,425,273	0.1471	0.2037	0.2523	0.1052	0.185	0.2037	0.2387	0.0537	0.207	0.2037	0.1975	0.0095
AAM-178,542,100	0.1918	0.2231	0.243	0.0512	0.2694	0.2231	0.1787	0.0908	0.2259	0.2231	0.2178	0.0081
AAM-178,542,104	0.1642	0.225	0.2761	0.1119	0.2058	0.225	0.26	0.0542	0.2289	0.225	0.2175	0.0114

(green)	Baseline Best BV score
(cyan)	Sensitivity Analysis best range score

All of the AAM options presented in the sensitivity analysis are viable AAM system designs just by the nature of the VE analysis. The PM would be using the sensitivity analysis to help balance the risks associated with picking the final design. Additional detailed analysis would follow-up the initial design to confirm risk indicators noted in the sensitivity analysis.

3.3.2.2 DoE approach

A strategically planned and executed sensitivity analysis may provide a great deal of information about the effect on a response variable due to one or more factors. Initial analysis may involve holding certain factors constant and altering the levels of another variable.

The OVAT approach to process knowledge is, however, inefficient when compared with changing factor levels simultaneously. If the PM had additional concerns over multiple technologies, schedule or cost factors impacting the design at once, the PM would direct the design team to evaluate multifactor changes to the design with DoE instead of the single factor OVAT methodology. DoE allows for multiple input factors to be manipulated in determining their effect on a desired output (response). By manipulating multiple inputs at the same time, DOE can identify important interactions that may be missed when experimenting with one factor at a time.

For each factor under consideration, the extreme but realistic high and low levels to be analyzed must be selected. The extreme levels selected should be realistic, not unreasonable. The factors and levels are entered into the analysis design matrix and STMI conduct the BV analysis to provide the result for analysis.

The American Society of Quality (ASQ) maintains an excellent website (http://asq.org/learn-about-quality/data-collection-analysis-tools/overview/design-of-experiments.html) within which design teams can learn about applying DoE principles and utilize template DoE spreadsheets which allow fairly fast-turn DoE analysis. Utilizing the ASQ DoE template, Figure 25 illustrates a 3-factor DoE sensitivity analysis approach with the deterministic STMI AAM system design data applied. Using the "best value" AAM-11,069,111 design from Figure 22 as the system base, and maturation cost, unit cost and expected lifecycle time as example factors with the same ranges as

Design of Experiments

Description

This template illustrates DOE or Design of Experiments sometimes called a Statistically Designed Experiment. A detailed discussion of DOE can be found at www.ASQ.org

Learn About Design of Experiments

Instructions

- Enter the High and Low levels for factor A, B and C. Names and Levels are recommended but not required.

Factor Name	Factor Letter	Low Setting	High Setting
Maturation Cost ($K)	A	99000	132000
Unit Cost ($K)	B	94.5	126
Lifecycle (Years)	C	15	30

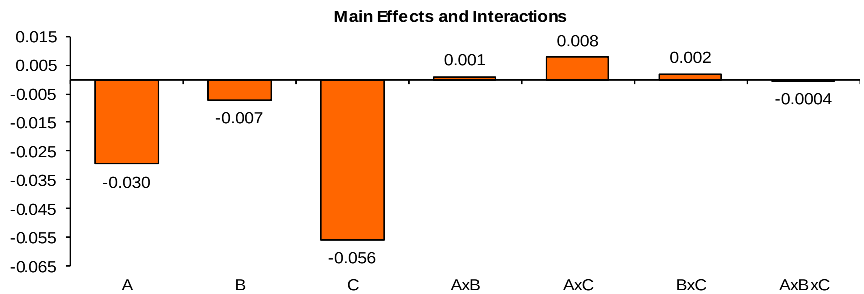
- Run each of the eight combinations in random order using the Run Order Column.
- Collect at least one output measurement for each of the eight runs. Five are recommended.
- Review the bar graph to identify the factors or interactions having the greatest effect.
- If the effect of an interaction is shown to be large, use the interaction plots to determine the best settings that will optimize the output.
- Detailed calculations can be displayed by clicking on the radio button for any factor or interaction.

Learn More

To learn more about other quality tools, visit the ASQ Learn About Quality web site.

Learn About Quality

	Run Order	Maturation Cost ($K)	Unit Cost ($K)	Lifecycle (Years)	AxB	AxC	BxC	AxBxC	Trial 1 (BV)
1	6	99000	94.5	15	1	1	1	-1	0.2626
2	8	99000	94.5	30	1	-1	-1	1	0.197
3	1	99000	126	15	-1	1	-1	1	0.2522
4	4	99000	126	30	-1	-1	1	-1	0.1911
5	2	132000	94.5	15	-1	-1	1	1	0.224
6	5	132000	94.5	30	-1	1	-1	-1	0.1744
7	3	132000	126	15	1	-1	-1	-1	0.2164
8	7	132000	126	30	1	1	1	1	0.1698



Select Factor or Interaction for Calculation Details:

- A
- B
- C
- A x B
- A x C
- B x C
- A x B x C

High (+1) settings:

average (0.2626 0.2522 0.1744 0.1698) = 0.21475

Low (-1) settings:

average (0.197 0.1911 0.224 0.2164) = 0.20713

Effect:

0.2148
- 0.2071
0.0076

A x C Interaction

		C LO	C HI
A LO	1	0.2626	0.197
	2	0.2522	0.1911
	Avg	0.2574	0.1941
A HI	1	0.224	0.1744
	2	0.2164	0.1698
	Avg	0.2202	0.1721

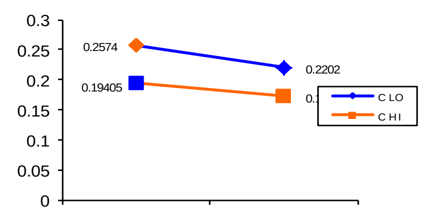


Figure 25: DoE ASQ template, sensitivity analysis for deterministic AAM example

used in the OVAT analysis, the DoE sensitivity analysis yielded the following conclusions:

1. The lifecycle time (Factor C) yielded the highest impact on the BV scores. The AAM-11,069,111 design becomes a less attractive option from a BV standpoint the longer the system lifecycle is drawn out.
2. When maturation cost (Factor A) and lifecycle time (Factor C) change, they have the highest interacting effect, which is fairly minimal compared with the individual factors.
3. All three factors taken together have very little interacting effects.

As single trial of the DoE approach was conducted due to the deterministic nature of the system design equations. If the system design and/or database incorporated data variability (stochastic), multiple trials of the DoE would be conducted and averaged to generate the complete DoE analysis.

3.3.2.3 Sensitivity Analysis with optimizer

As a precautionary note, the sensitivity analysis should be recompleted with the “all-option” STMI process to be able to address the same system of DoE interest run after run. Utilizing metaheuristic optimizer like the GA may yield different system designs due to the random analysis factors inherent within the process. If the metaheuristic did not select the system design of interest being examined by the multi-factor DoE analysis, it would interfere with the overall analysis.

3.3.3 Incremental delivery analysis

The STMI optimization for BV can also be adapted to generate incremental deliveries for a proposed system as customer requirements are updated or additional technologies are identified to be inserted into a system design. By changing the optimization threshold or evaluating updated technologies, the STMI process can strive to meet the new customer requirements, and lay out a new STP. This would allow the PM team to layout incremental upgrades to the baseline system design and identify key changes in the technology mixture that must be matured to meet the upgraded system capability.

4 Methodology and case study

Chapter four presents a case study example of the STMI process through all three process steps to build a long term Strategic Technology Plan (STP) to meet a long term customer need. Each step of the STMI methodology will be conducted in the context of the case study scenario. The case study scenario background will be provided to set the stage for STMI operation by a PM team examining options to meet the customer need (macro level) and also include a specific system design to become one of those options considered (micro level). The STMI process will be used to create a common “best value” evaluation criterion across all options and to present a technology set recommendation for inclusion into the capability STP.

The case study is meant to be a detailed example of the STMI methodology, providing additional insight into the process steps compared with the AAM example provided in Chapter Three.

Case study: National electric grid Frequency Regulation (FR) options

4.1 Scenario background

The Federal Government’s growing concern for national power grid Frequency Regulation (FR) has jumped dynamically as renewable energy sources (solar and wind) have been increasingly integrated in the regional power supply mix. However, solar and wind are not constant and reliable sources of power. The variable nature of these renewable sources causes significant challenges for the electric grid operators because other power plants (usually fossil fueled power plants) need to compensate for the variability. During the day, wind power can be a few gigawatts (GW) at some moments and only a few megawatts (MW) and even zero at others, as illustrated in Figure 26 Similarly, Figure 26 also indicates solar power is generated only during the daytime and varies when clouds pass by[278]. A 2007 report from California Independent System Operators (CAISO) indicated that with the addition of renewable energy sources and their inherent power variability (due to clouds, day/night cycles, wind sources), there would be a need in California alone for 730 MW of additional regional FR capability by 2015 and growing at a rate of 120 MW per year[277].

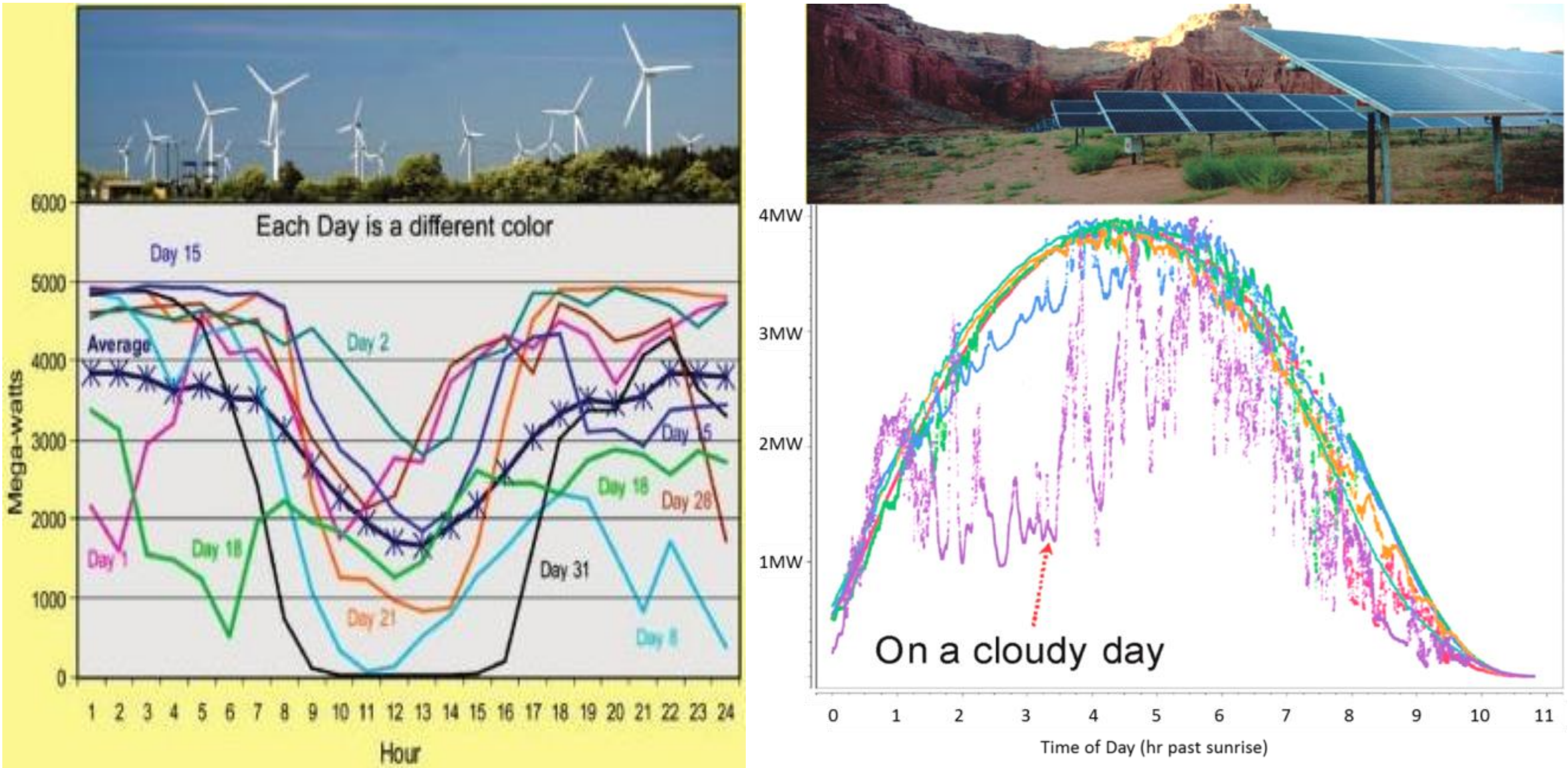


Figure 26: Daily profiles of wind power in Tehachapi, California and 5 MW solar power array output over 6 days in Spain

FR involves Independent System Operators (ISOs) that operate regional power grids to contract with smaller power providers to help balance loads on the grids under their control. On a perfect grid, consumer electrical demand would match utility electrical supply, allowing ISOs to keep the standard electrical grid frequency at 60 Hz. But as electrical demand waxes and wanes during daily cycles, primary power suppliers take time to ramp-up or ramp-down power plant output. This causes variation in the 60 Hz standard electric frequency, and any significant variation can cause damage to utility and customer electrical systems. However most fluctuations are of short duration since primary power utilities take 10-20 minutes to ramp up or down large generating systems. Therefore, FR requires mega-watts of power instantaneously, with 98% of the fluctuations being handled within 15 minutes[279]. Figure 27 illustrates a daily power grid cycling operational scenario and areas were FR is required to help balance the load between power plant output changes[281]. Once the variability of renewable energy sources is included in the daily power grid cycle, FR becomes a critical feature to maintain the grid. Table 11 illustrates the basic threshold requirements for a FR power system.

Another key attribute is that ISOs pay FR system owners for the power that is pulled or pushed into the grid to maintain the grid frequency. Although the payment per Megawatt (MW) per year varies by ISO, it is typically $175,000 to $250,000, with an average value of $212,500[280].

To examine this issue, the PM's company was commissioned to do a study by the US Department of Energy (DOE) and Federal Energy Regulatory Commission (FERC) exploring the best near term (0-5 yrs) methods for national power grid FR. DOE and FERC want a recommendation of technologies that can be developed and implemented within those time frames. Key trade studies will include relaxed system mass and geometry requirements, FR capability compensation and composite material costs. A data sensitivity analysis is also requested to examine system development, unit and lifecycle cost variation by 20% to identify key areas that must be watched for cost impacts. Finally, a future upgraded FES that is smaller and lighter by 25% for potential integration into vehicle and mobile applications.

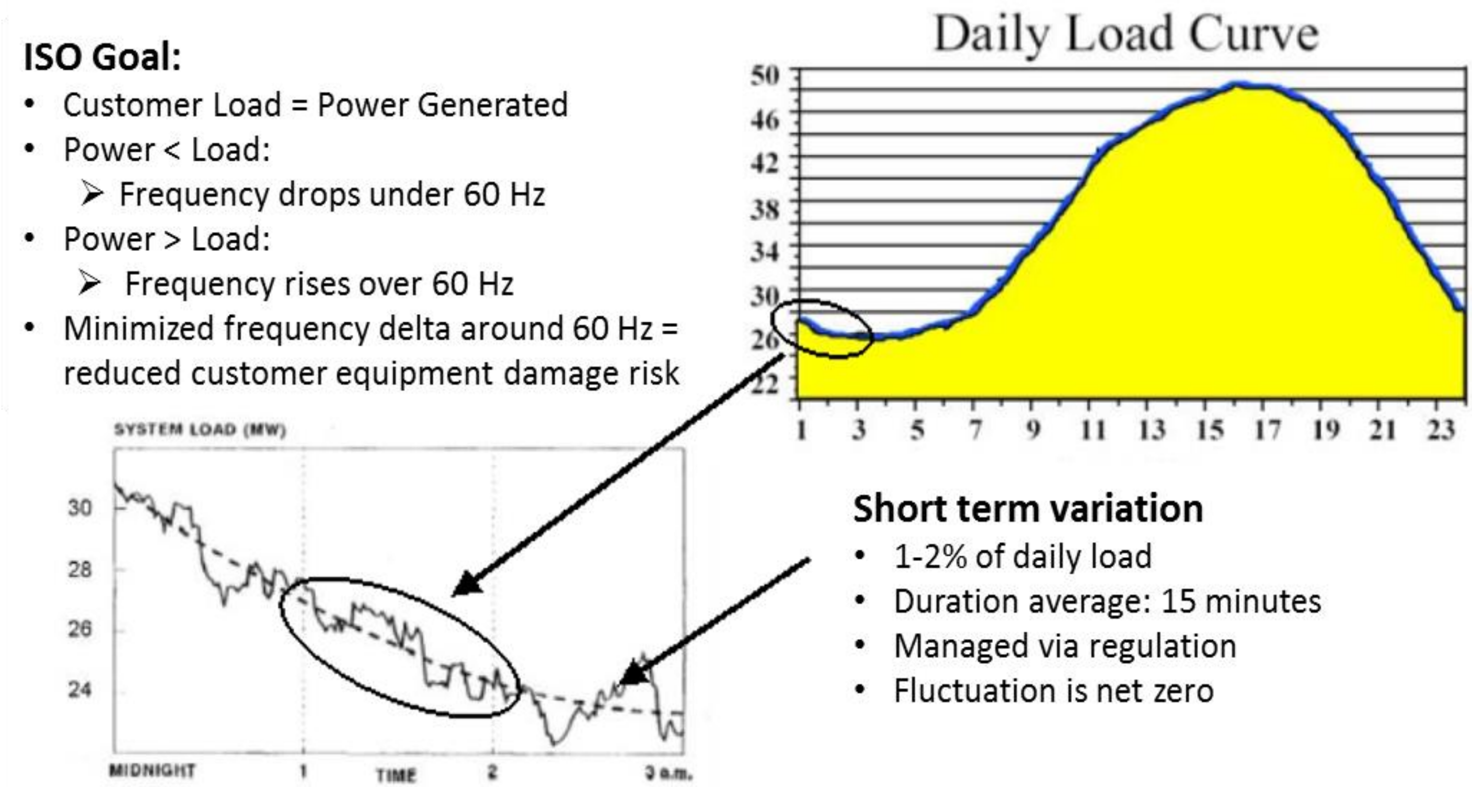


Figure 27: FR requirements in a 50MW daily power cycle operational scenario

Table 11: FR system requirements, 1000MW market

Requirement	Threshold level	Notes
Power reserve[282]	20 MW for 15 minutes (5MWh)	2% of 100MW
Response time[283]	Full reserve capability within 5 minutes	Based on ramp times
Cycles per day	48 power up + 48 power down cycles of 15 minutes each	Based on a 24 hr day cycle

The DOE and FERC want an unbiased analysis from a third party (non-utility) and insist that the STMI “best value” methodology be employed to create an “apples-to-apples” comparison of the technologies available when lifecycle costs are compared.

4.2 FR system options available

Current systems able to meet FR operational scenario have been reviewed in reports from the California Energy Storage Alliance (2010)[284] and Department of Energy (2013)[285] and are summarized in Table 12.

Table 12: Current FR system technologies

FR system	Power type	Typical ramp rate (% power in 5 minutes)	Round trip system efficiency
Combustion Turbine[286,287]	Generated	25.4-100%	31.5%
Pumped Storage Hydropower (PSH)[288,289]	Stored/ Generated	100%	81%
Compressed Air Energy Storage (CAES)[290,291]	Stored/ Generated	50%	55%
Lithium Ion Chemical Battery[292,293]	Stored	100%	80%*
Dry Cell Chemical Battery[294]	Stored	100%	86%*
Sodium-Sulfur Chemical Battery[295]	Stored	100%	80%*
Flywheel Kinetic Battery[296,297]	Stored	100%	85%

*Does not include battery temperature conditioning losses of 1-3%

Pumped Storage Hydropower (PSH), chemical battery arrays and kinetic Flywheel Energy Storage (FES) technologies are energy storage technologies uniquely capable to handle high load, short duration FR power requirements. These energy storage technologies can rapidly recycle electricity from the grid by absorbing it when the supply is greater than demand, and injecting it back when needed to meet demand, thus helping to stabilize the frequency of the grid. These responsive technologies have the ability to inject or absorb their full load rating instead of having a reserve capability due to system ramp rates. Figure 28 provides a 2010 current worldwide summary of energy storage technology use[298]. Figure 29 provides an illustration of FR system operational scenarios.

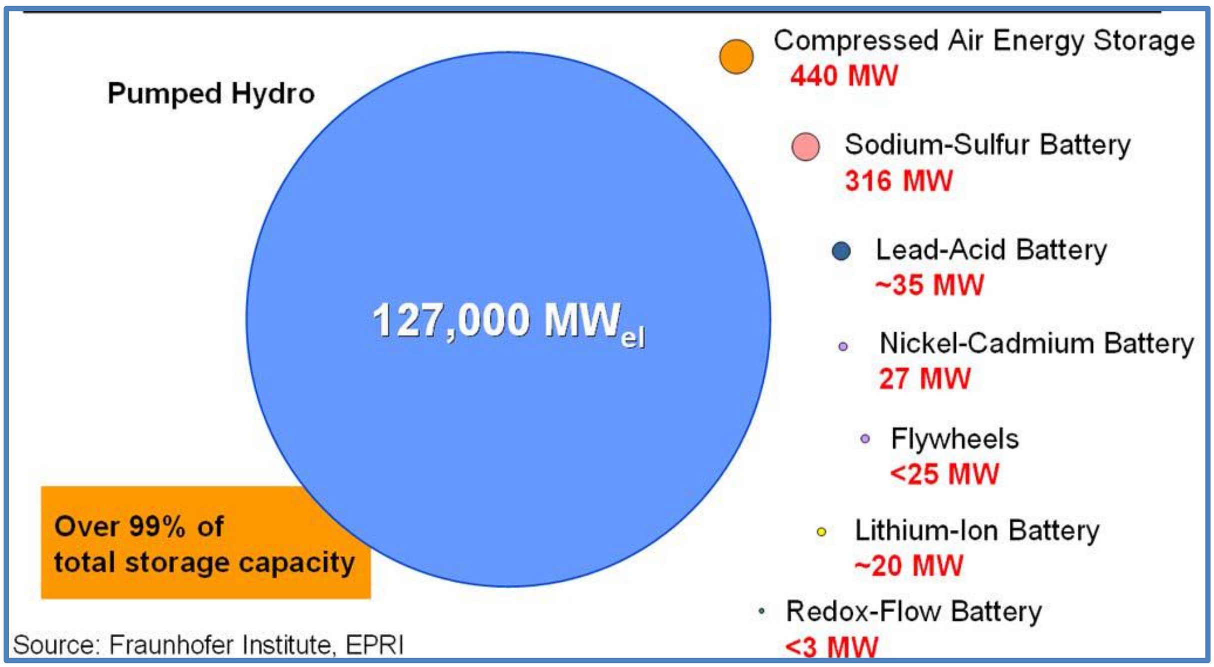


Figure 28: Worldwide installed storage capacity for electrical energy

Combustion Turbine: As the most common type of FR capability, combustion turbines generate power on demand, typically utilizing natural gas as a fuel source. The main advantages are a highly reliable, established technology that can be incorporated into existing power plant facilities with the ability to be powered up and down rapidly when operation is required. Disadvantages include slow ramp-up times which require excess capability to be available to meet FR requests, low efficiencies, high carbon footprint, and medium level of capital building costs.

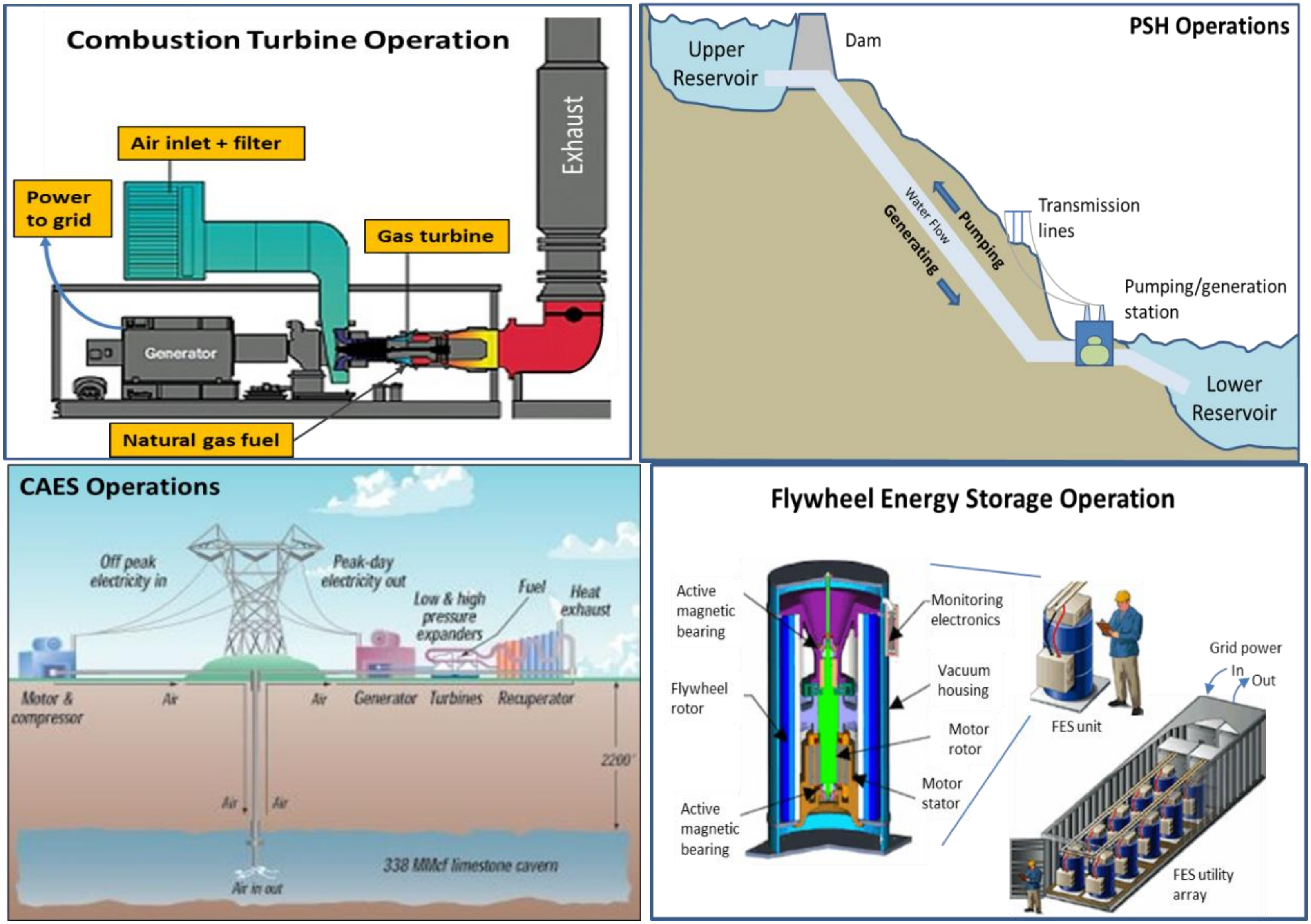


Figure 29: FR systems operation diagrams

Pumped Storage Hydropower (PSH): PSH operates by moving water between two reservoirs at different heights by means of a pumping system and a hydroelectric generation plant. Electricity is generated from the kinetic energy of water as it flows downhill through a generator turbine and is stored as potential energy when it is pumped uphill. Most PSH systems are located in hilly or mountainous regions with sufficient rainfall or access to a water resource (river or lake). Advantages are high capacity, low maintenance and long operational life. Drawbacks are its high initial capital cost, fixed geographical and environmental restrictions placed on a reservoir or dam site, and sensitivity to drought conditions.

Compressed Air Energy Storage (CAES): In a CAES system, a large underground space (usually an unused mine) is used to contain air at a high pressure. Excess power from the grid is used to compress air and pump it into the storage space. When power is needed, the air is released, expanded and used to drive power turbines. Current CAES systems are located above old mines or natural caverns which serve as the compressed air storage facility. Advantages are similar to PSH with moderate capacity, low maintenance and long operational life. Disadvantages include fixed geographical restrictions/access, and dealing with efficiently expanding the compressed gas (usually coupled with a combustion turbine in a "supercharger" mode, reducing fuel requirements by 40%)[299].

Electrochemical Battery Energy Storage: An electrochemical battery is a device capable of either deriving electrical energy from chemical reactions or facilitating chemical reactions through the introduction of electrical energy. FR grid scale electrochemical batteries absorb excess electricity directly from the grid when the power load is too high, and returns the electricity directly to the grid when power load drops too low. Current grid scale systems include Lithium-ion (A123 technologies), Dry-acid (Xtreme Power Inc.) and molten sodium-sulfur (EaglePicher Tech). Advantages include medium to high energy densities, low cost, scalable, and relocateable based on utility needs. Disadvantages include limited depth of discharge, decreased performance over time, high levels of monitoring/maintenance, temperature sensitivity, environmental and safety hazardous materials, unknown exact charge level, and chemical battery replacement after 4-7 years.

Flywheel Kinetic Battery - Flywheel Energy Storage (FES): FES systems absorb excess power from the grid and store it as kinetic energy in a high speed (16,000-60,000 rpm) spinning rotor spinning in a near frictionless vacuum enclosure. A high efficiency motor-generator provides the transfer between electrical and kinetic energy to and from the grid and spinning rotor. Like chemical battery systems, FES units can be placed where ever rapid reaction FR capability is required. Advantages include high energy densities, high power throughput, fast power response time (20 milliseconds)[300], low maintenance, negligible environmental impact, temperature insensitivity, exact charge status (rotor rpm = energy) and 20+ year operational lifecycle[301] with unlimited deep charge and discharge cycles. Disadvantages include high rotor material costs, scalability of power and energy components, and standby frictional power losses.

4.3 Micro analysis: Kinetic FES System

The PM's team subdivided the FR system analysis and assigned the kinetic FES system analysis to this research case study. All of the individual FR systems will then recombine for the final analysis and recommendation in the Macro-level STMI process in section 4.3.3.3.

FES system background

The idea of storing energy in a rotating wheel has been utilized since 2400 BC, when Egyptians used hand-turned stone wheels to craft pottery and millers used powered millstones to crush grains[302]. In the years between 1800 and 1950, traditional steel-made flywheels gained application areas in train, car and bus transportation, and smoothing power draw from electrical sources. Modern FES systems began in the 1970's and began with systematic improvements utilizing high strength composite materials, magnetic lift bearings, efficient power electronics and modern control systems.

Flywheel based energy storage applied to electrical grid FR management has also become a potential “green energy” alternative. FES systems provide a rapid, low impact response capability to match utility fluctuations in power more effectively and reliably than either chemical battery systems or rapid cycling natural gas fired generators[303]. Modern FES systems are environmentally friendly, incorporating zero hazardous chemicals, generating a zero CO_2 footprint, and have round trip energy efficiency of over 85%[304]. For customers comparing system lifecycle costs, the 20+ year FES design life with unlimited power cycles and nearly maintenance free operation is very attractive.

For comparison, only one Flywheel company, Beacon Power[305], has expanded into the larger, flywheel technologies usable for commercial high power FR vs. smaller applications, such as Uninterruptable Power Supply (UPS), as illustrated in Table 13. Beacon Power’s Smart Energy 25 flywheel design will be the “immediately available” FES system while the case study FES micro level design and optimization is conducted for the near technology development system improvements.

Table 13: Commercial flywheel technology providers

Tech Company	Flywheel Application	Power Rating (KWh)	Rotational Speed (max)	Flywheel Materials
Beacon Power[306]- Smart Energy 25	Frequency Regulation	25	16,000 rpm	Carbon Fiber / Fiberglass Rim w/ Steel Rotor
KineticTraction[307]	Kinetic energy recovery	1.5	36,000 rpm	Carbon Fiber
Vycon[308]	UPS	0.83	36,750 rpm	Steel
PowerThru[309,310]	UPS	0.53	56,000 rpm	Carbon Fiber
ActivePower[311]	UPS	0.33	30,000 rpm*	Steel
Temporal Power[312]	Frequency Regulation	50	20,000 rpm*	Steel

* Approximation based on material strength, size and power rating

4.3.1 STMI stage 1: Requirements, functions and technology database

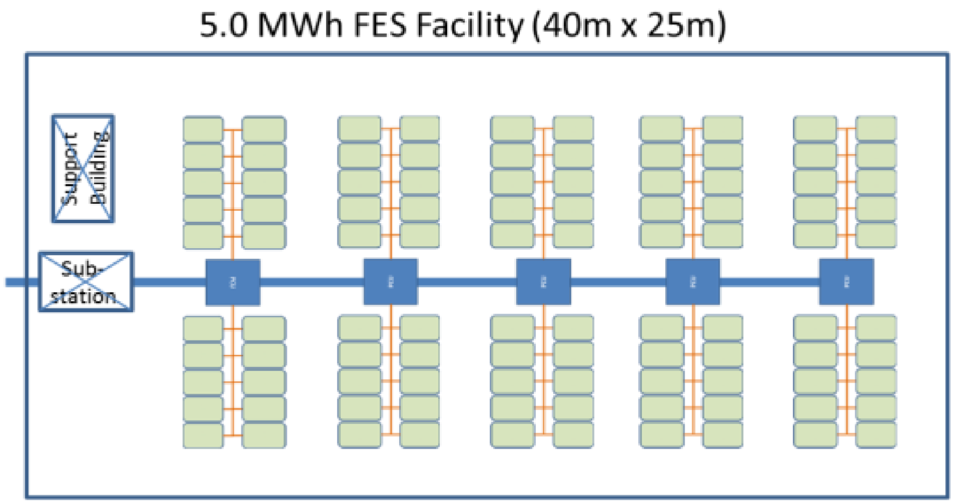
4.3.1.1 FES design requirements and constraints

In examining the FES FR facility for this case study, the PM and customer have established a few baseline assumptions and Key Performance Parameters (KPPs) used to address the requirements in Table 11 and are summarized in Customer Requirement Document (CRD) on Table 14.

Table 14: Customer Requirements Document (CRD) summary

Reference	Category	Requirement/constraint description	Threshold value
1.1	Geometry	FES kinetic rotor radius	0.45m
1.2	Geometry	FES system length = 3 x rotor diameter	2.7m
2.1	Safety	Metal rotor safety factor	40%
2.2	Safety	Composite rotor safety factor	25%
3.1	Efficiency	FES system round trip efficiency	85% (KPP)
4.1	Power	FES rotor sized for 50KWh +15% reserve	58.9KWh (KPP)
4.2	Power	FES motor/generator rated output power level	200KW (KPP)
5.1	Mass	FES system mass limit for 2Ton forklift transport at 80% load	1600kg (KPP)

First, the FES FR facility will be set up in a modular style array, similar to the Beacon Power facility in Stephentown, New York[313] pictured in Figure 30. Given the customer requirement for a 20 MW (5MWh) facility, the FES FR modules will be designed for a KPP power output of 200KW and a storage level of 50KWh with a 15% reserve to account for round trip electrical losses. This yields a FES FR facility requiring 100 individual FES units linked together as illustrated in Figure 30.



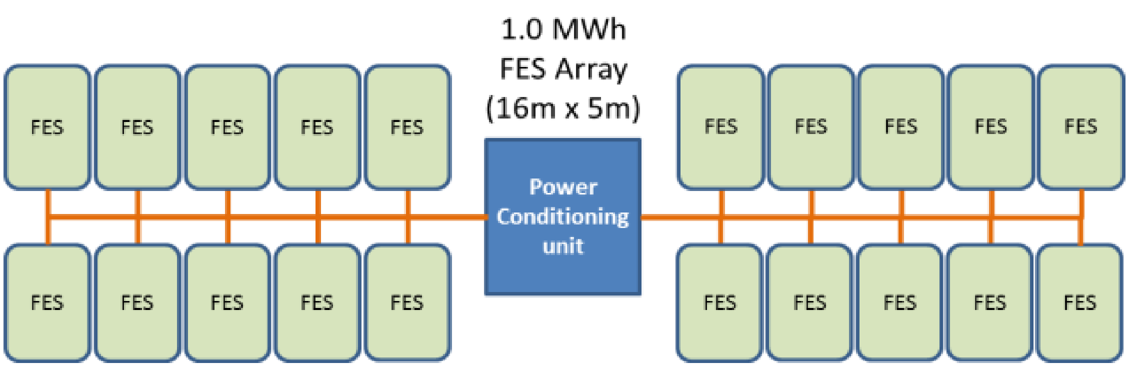


Figure 30: Beacon Power FES Facility and STMI Case Study FES Facility

Second, the individual FES units must be able to be lifted and repositioned with a standard light duty two metric ton forklift at 80% load. This provides an upper limit to the system mass KPP at 1600 Kg or 3528 pounds and addresses a key manufacturing, installation and maintenance cost reduction that plagued Beacon Power systems (just the Smart Energy 25 FES rotor unit weighed in over 2500 lbs each with the FES unit weighing in over 5000lbs and required loading cranes to move each unit)[314].Using the 2T forklift also imposes a PM recommended physical size limit on the FES system for the length to be less than three times the rotor diameter.

Third, the FES rotor units will have an embedded 25% safety factor for composite material technology and 40% safety factor for metal component technologies based on the material tensile strength resistance to rotor hoop and radial stress. This is based on the historic catastrophic failure modes for composites (many smaller, rotational fragments with low energy) and metal alloys (few large, translational sharp edged fragments with high energy) and their potential for penetrating the FES containment shell[315].

Fourth, the FES unit will have a KPP minimum 85% round trip energy efficiency to meet levels offered by other advertised FES systems. This efficiency is defined as energy put into the motor/generator from the utility grid, transferred to the flywheel, stored in the flywheel, pulled from the flywheel by the motor/generator and then returned to the grid through the motor/generator. The rotor system will be sized 15% higher than the 50KWh (50/0.85 = 58.9KWh, rounded up) to account for potential losses. Systems with common energy loss areas are the bearings, vacuum environment, control system and efficiencies of the motor/generator.

Note: Any FES system with round trip energy efficiency greater than 85% will be given an “earning bonus” in the operations costs based on the FR payment (lowers ops cost for system). For example, when comparing an 85% and 92% efficient FES, at 92% efficient system will have an additional 4.1 KWh or 16.4 KW available on a baseline 50KWh, 200 KW FES system design. Based on FR payment average noted in section

4.1 ($212.5/KW/yr), the 92% efficient FES would earn $3485 more per year (noted as negative operations cost) over the baseline 85% efficient FES design.

4.3.1.2 FES system overview, key parameters and system models

The core concept to understand regarding flywheels has to do with the conversion of energy. FES energy is stored as kinetic energy, for however long it may be required. To accomplish this, a rotor spinning inside a casing which provides vacuum and structural support, spins at higher angular velocities as more energy is stored. As energy is removed the angular velocity is consequently decreased. To do this and create a complete system that is useful for energy storage, several components are required, including the flywheel itself, the vacuum enclosure, bearings, power transmission motor/generator, cooling, and system controls. For the purposes of this STMI case study, a limited selection of potential technologies listed in Table 15 for the FES system design illustrated in Figure 31 will be examined.

Based on the number of technology options, there are up to 1800 potential FES design combinations to be analyzed. Final unit costs will be based on costs to build 100 units. Installation and power conditioning electronics for the full FES FR facility are assumed to be two times the final unit costs[316].

Flywheel design and material

The flywheel is undoubtedly the heart of the FES system. Also commonly called rotors, flywheels can vary in shape, size, and material. One way of characterizing its shape depends on its geometry, and therefore moment of inertia. This is commonly referred to as the ‘shape factor’, ‘K’, which is a dimensionless quantity. The amount of energy ‘E’ stored in a flywheel varies linearly with moment of inertia ‘I’ and with the square of the angular velocity ‘ω’, which can be calculated with Equation 14 and Equation 15.

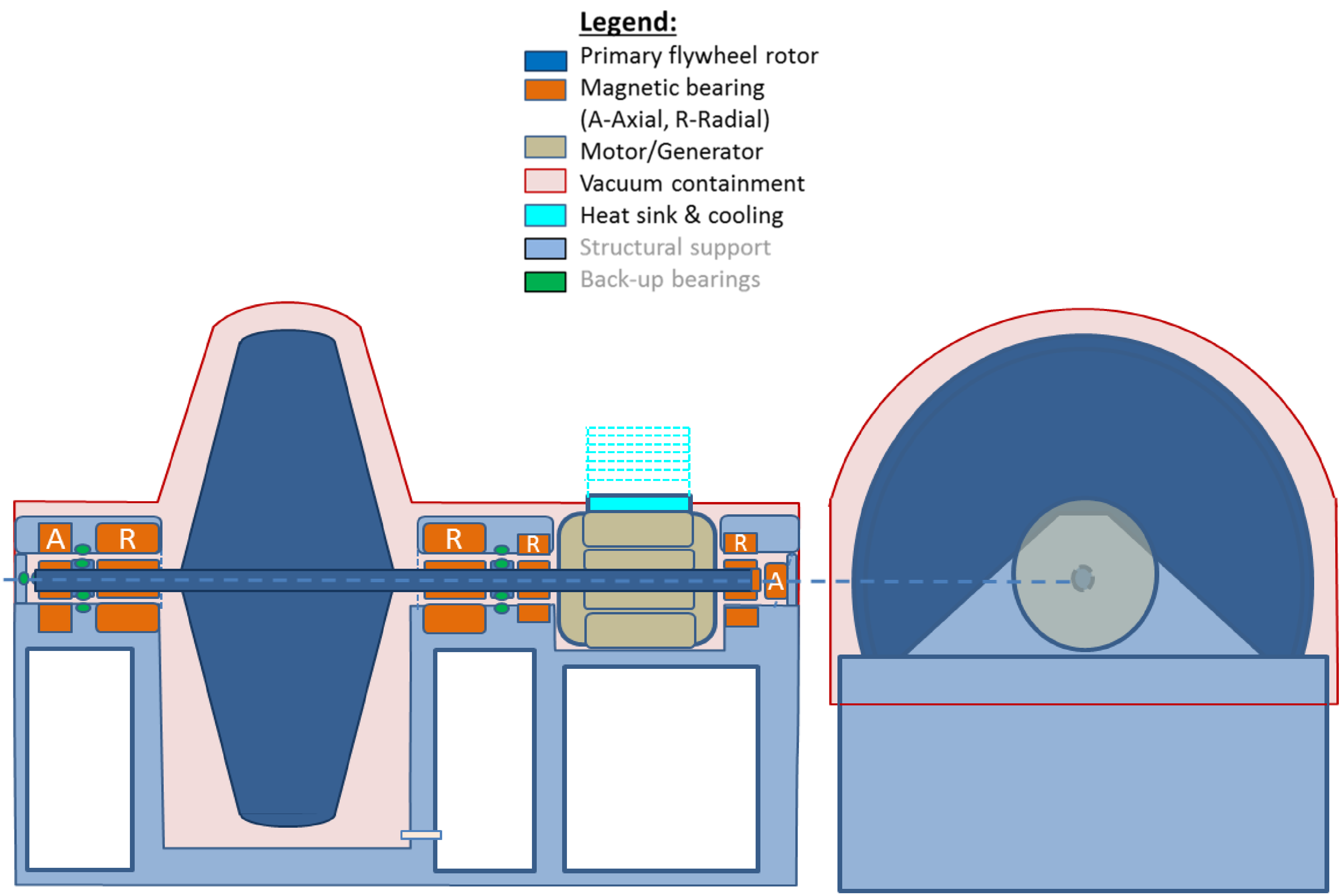


Figure 31: Key FES functional areas

Table 15: FES functional areas and initial technology options

Functional Area	Technology						
	1		2	3	4	5	6
Flywheel design	Disk	Hub & Cylinder	Advanced 3-D	Advanced 3-D			
Flywheel material	Steel ASTM A514	Aluminum 2014-T6	Composite Laminate (E-glass)	Composite Laminate (S-glass)	Composite Laminate (AS4C)	Composite Laminate (IM10)	Composite Laminate (Advanced CNT)
Magnetic bearings	Permanent Neodymiun N42	Permanent Samarium Cobalt-24	Ferrite Ceramic class-5	Active magnetic bearing			
Motor/ Generator	Standard (93% efficient)	Efficient EPAct (95% efficient)	Premium NEMA (96% efficient)	Ultra-NEMA (97.5% efficient)			
Heat sink & cooling	Passive	Active (fan)	Active (fan) + TEG				
Vacuum containment	Active pumped	Sealed vacuum					

Equation 14: Flywheel kinetic energy $E = \; KI\omega^2$

Where common ‘K’ shape factors are tapered disk (1.0), constant stress disk (0.931), constant thickness disc (0.606), thin rimmed cylinder (0.5), and constant stress bar (0.5)[317].

The moment of inertia is a physical quantity, which depends on the mass and shape of the flywheel. It is defined as the integral of the square of the distance ‘x’ from the axis of rotation to the differential mass ‘dm_x’.

Equation 15: Moment of Inertia $I = \int_0^m \int x^2 \, dm_x$

The solution for classic flywheels of mass ‘m’ and inner and outer radius ‘r’ will be[318]:

Equation 16: Moment of inertia for a cylindrical mass $I = \frac{1}{2} m r_o^2$

Equation 17: Moment of inertia for a hollow circular cylinder $I = \frac{1}{2} m (r_o^2 + r_i^2)$

Equation 18: Moment of inertia for a solid cone $I = \frac{3}{10} m r_o^2$

Since the energy stored is proportional to the square of angular velocity, increasing the angular speed increases stored energy more effectively than increasing mass. The speed limit is set by the stress developed within the wheel due to inertial loads, called tensile stress ‘σ’, where the two primary loads that must be checked are radial and hoop tensile stresses[319]. Lighter materials develop lower inertial loads at a given speed, therefore composite materials, with low density and high tensile strength, are excellent candidates for storing kinetic energy[320].

For the purposes of the FES design, the rotor outer diameter will be set at 0.45 meters to balance maximum rotational speed, rotor stability and available motor/generator operating speed ratings. Rotor material tensile strength and density are the primary factors contributing to the rotor geometry and mass. Development funding is based on rotor shape complexity. Rotor unit costs are based on material and manufacturing costs. Lifecycle costs are minimal since the rotor is designed for 20 year operational life with no serviceable parts.

Details of the rotor designs will be provided in Appendix B and will be the source for the technology database.

Vacuum enclosure

For most flywheel systems, some type of housing is required to keep a vacuum, to eliminate atmospheric drag on the flywheel, and to provide a shield for contact and also from possible rotor failure. In FES designs where speeds can reach as high as 60,000 rpm, atmospheric drag can contribute significant losses. The aerodynamic drag acting on the flywheel can be expressed as shown in Equation 19 where 'Ta' is the torque experienced by the flywheel, 'ρ' is the density of air, ω is the angular velocity, 'r' is the radius, and 'C_m' is a dimensionless coefficient relying on Reynolds number, Knudsen number, and the Mach number (relation of the radius, angular velocity and speed of sound).

Equation 19: Rotational Drag in an atmosphere $$T_a = \rho_g \omega^2 r_0^5 C_m$$

For the purposes of the FES design, the main impact of the vacuum enclosure is the physical mass (based on the geometry of the flywheel components and rotor failure mode), parasitic drag from residual atmosphere, and power required to maintain the required vacuum level (active pump system). Development funding required is based on the complexity of the vacuum system and "hardness" of the vacuum emplaced on the system (design complexity). Lifecycle impacts focus on any operational power consumption and maintenance requirements (active systems require routine maintenance and servicing, while sealed systems can be remotely monitored and inspected yearly).

Magnetic Bearings

To minimize the rotation friction generated by potential contact between the rotor shaft and supports, a bearing system is required. Due to the high speed nature of the FES rotor operating in a vacuum and the need for very low frictional losses, high speed metal and ceramic bearings were ruled out due to 1-3% frictional losses, lubrication difficulties in vacuum and increased maintenance requirements of routine bearing inspection and repacking[321]. Permanent magnetic bearings and active electromagnet bearings are considered for the FES system to suspend the rotating rotor and shaft in a near frictionless environment. Sizing of the permanent magnetic lift system is based on the magnet's field strength, measured in megagauss-oersteds (MGOe), and the cross-sectional bearing area of the ring magnet (sizing based on the rotor shaft cross-section geometry). The sizing "rule-of-thumb" for permanent magnetic lift is noted in Equation 20 and Equation 21[322] and includes a 25% safety factor.

Equation 20: Magnetic bearing lift capability (radial) in Kg:

$$1.25x\,\frac{0.1\ kg/cm^2}{1\ MGOe}\,x\ Field\ strength\ x\ Cross\ section\ of\ the\ shaft\ bearing\ area$$

Equation 21 Magnetic bearing lift capability (axial) in Kg:

$$1.25x\,\frac{0.14\ kg/cm^2}{1\ MGOe}\,x\ Field\ strength\ x\ Cross\ section\ of\ the\ shaft\ bearing\ area$$

Losses from a permanent magnet bearing system would center on the axial mechanical or active magnet bearing required for stability purposes[323]. Losses for the stabilizing mechanical or active magnet bearing would approach 25w/hr, resulting in a 0.05% power draw for 50 KWh FES (99.95 efficient component).

Active bearings are much smaller in size and mass for the field strength produced compared with permanent magnets, but have a larger number of complex components for operation. Power draw for active magnetic bearings for the rotor mass support is approximately 1 watt per 1.8 kg[324] and sizing for load is available from commercial websites like www.synchrony.com. For a 300 Kg FES rotor, a 167 Whr power draw could be expected, resulting in a 0.34% power/hr for a 50 KWh FES (99.66% efficient component).

Development funding required is based on the complexity of the active magnetic bearings and integrating either type of magnet bearing system. Unit cost for permanent magnetic bearings is principally the physical magnet rings, while the active magnet system requires ten electromagnets, five displacement sensors, one evaluation unit, one control unit, five power amplifiers, one uninterruptable power supply and one constant current source[325]. Lifecycle impacts focus on operational power consumption and maintenance requirements (active systems require routine maintenance, while permanent systems can be remotely monitored and inspected as needed).

Motor/Generator

The motor/generator and power electronics form the energy transfer system of the FES, transferring electrical grid power to and from mechanically stored energy within the flywheel. When acting as a motor, the electric energy supplied to the stator winding is converted into mechanical energy, increasing the speed of the flywheel. In generator mode, kinetic energy stored in the rotor is transformed into electrical energy. A motor/generator with both low no-load losses and low load losses is needed, as electrical energy has to be converted to mechanical energy and vice versa at high efficiencies to make the FES system competitive for FR applications.

The flywheel motor/generator incorporates a radially polarized permanent magnet (PM). PM machine uses permanent magnets to provide field excitation, providing high rpm, high efficiency and reduced size for an equivalent power when compared with other types of machines such as induction and switched reluctance machines[326]. The motor/generator consists of a rotor assembly and a stator assembly. The rotor assembly contains the permanent magnets, which are constrained by a high strength steel retaining sleeve. The sleeve also provides the structural connection to the flywheel shaft. The three-phase stator is conventionally wound, allowing a simple low cost construction. To ensure effective operation in the vacuum environment, the motor/generator design was optimized to minimize rotor losses (high efficiencies).

Due to the unique requirement for high rpm speed (25,000-35,000) and high input/output power (200kW, 260 HP), Commercial off the Shelf (COTS) motor/generator systems are virtually nonexistent. Therefore, for the purposes of this study, parametric scaling of existing PM motor/generator systems is used to estimate mass and unit costs (see Appendix C for PM motor details). Development funding is based on a factor of 10 vs. the unit cost and TRL ranking. Lifecycle impacts focus on operational power consumption and maintenance requirements, where higher efficiency motor/generators require less operational costs and maintenance costs.

Heat sink/Cooling

Even the most highly efficient motor/generator will generate a certain amount of waste heat, which in a vacuum environment, must be removed through conduction and dispensed outside the vacuum enclosure. Three actively cooled designs are offered for the FES analysis to allow trade-off of heat sink size and fan power consumption. The third design includes a set of ten Thermoelectric Generator (TEG) power cells that captures a 200w portion of the waste heat and converts it to power the blower fan and control electronics[327].

External heat sink temperature levels are targeted at 200 ℃ to minimize potential structural material damage and external fire hazards[328]. The heat sink exchanger is designed to sit on top of the motor/generator. Designs of the three thermal control systems will be based on designs at www.heatsinkcalculator.com and are documented in Appendix A. Included within the heatsink/cooling cost, mass and power budget is $1000, 10 kg, and 150 watts for control electronics and sensors.

Development funding required for the cooling is based on the complexity of the simpler passive cooling system vs. the active design. Unit cost is based on material costs for the copper heatsink and/or cooling fan. Lifecycle impacts focus on operational power consumption, fan and electronics replacement after 10 years (100,000 hrs MTBF - Mean Time Before Failure) and maintenance requirements (routine cleaning of the heat sink radiator and/or fan units).

4.3.1.3 Technology database

The main purpose for Technology database is to record the key elements of the technologies to be evaluated and to apply any parametric estimates across all data entries. This allows the FES technologies to be compared consistently against each other for all potential designs.

In building the technology database, initial analysis into certain technology areas often needs to be done for a sub-component design prior to the final technology database build. In the case of the FES system, initial analysis was required on the kinetic rotor and motor/generator to conduct sizing and mass determination. The initial analysis adhered to the customer requirements and constraints and actually became a "first cut" of the rotor technology options.

The data entries for the supporting FES technologies (bearings and e-glass composite vacuum enclosure) are parametric based calculations with inputs from the mass, length and power consumption of the rotor and motor/generator. Structural support (non-vacuum enclosure) is estimated at 25% of the combined rotor and motor/generator mass. Back-up chaser bearings, which provide emergency support for unaccounted for rotor dynamics or power failure of the active magnet bearings, are included within the structural mass. Detailed notes on the parametric assumptions are provided in the detailed technology database in Appendix D.

FES Rotor: In the rotor sub-component analysis, seven referenced rotor materials, based on tensile strength, density and Poisson's ratio (*=approximated), were matched against three separate rotor technology designs.

1) Aluminum 2014-T6 alloy (414 MPa, 2.80 g/cm^3 and 0.33)[329]
2) Steel ASTM A514 alloy (690 MPa and, 7.85 g/cm^3 and 0.29)[330]
3) E-Glass laminate composite (1408 MPa and 2.12 g/cm^3 and 0.28)[331]
4) S-2 Glass laminate composite (2000 MPa, 2.02 g/cm^3 and 0.28)[332]
5) AS4C carbon laminate composite (2206 MPa, 1.47 g/cm^3 and 0.25*)[333]
6) IM10 carbon laminate composite (3310 MPa, 1.47 g/cm^3 and 0.25*)[334]
7) In development Carbon Nanotube (CNT) reinforced laminate composite (65% AS4C + 35% CNT = 3728 MPa, 1.35 g/cm* and 0.25*)[335]

For the purposes of this case study, one material at a time was used in the rotor design model. Due to the high power level requirement of 50kWh for the rotor, many of the metal alloy options (aluminum and steel) exceeded the 1600Kg total FES mass threshold and had to be excluded as entries into the technology database. The final technology options for the rotors consist of 16 designs with steel and composite materials. Appendix B provides a complete listing of the individual rotor analysis for reference. Table 16 provides a summary of the rotor analysis, and successful rotors will be added to the STMI FES database for system analysis and optimization.

Table 16: FES rotor sub-component design specifications

Rotor	Mass	Material Cost	Shaft Length	Requirements and Constraints				
Designation	**(kg)**	**($/kg)[336]**	**(m)**	**1.1**	**1.2**	**4.1**	**5.1**	**Pass/Fail**
AL 2014-T6 (S)	8690	2.20	5.08					**Fail**
AL 2014-T6 (C&H)	5655	2.20	5.56					**Fail**
AL 2014-T6 (3-D)	2972	2.20	3.97					**Fail**
Steel A514 (S)	14147	1.80	3.05					**Fail**
Steel A514 (C&H)	9349	1.80	3.39					**Fail**
Steel A514 (3-D)	4914	1.80	2.44					**?**
E-glass (S)	1597	2.70	1.39					**Pass**
E-glass (C&H)	1073	2.70	1.55					**Pass**
E-glass (3-D)	668	2.70	1.32					**Pass**
S-glass (S)	863	16	0.893					**Pass**
S-glass (C&H)	602	16	1.03					**Pass**
S-glass (3-D)	426	16	0.819					**Pass**
AS4C (S)	703	23	0.953					**Pass**
AS4C (C&H)	484	23	1.09					**Pass**
AS4C (3-D)	358	23	0.823					**Pass**
IM10 (S)	465	64	0.697					**Pass**
IM10 (C&H)	323	64	0.794					**Pass**
IM10 (3-D)	273	64	0.553					**Pass**
CNT (S)	313	200	0.562					**Pass**
CNT (C&H)	213	200	0.623					**Pass**
CNT (3-D)	215	200	0.383					**Pass**

S = Solid Rotor, C&H = Hollow Cylinder & Hub, and 3-D = Advanced 3-D rotor.

Motor/Generator + Heat Sink: Mass and cost estimate are based on a varying efficiency, 200KW, high speed brushless permanent magnet (PM) motor/generator with sintered NdFeB PMs and laminated stator and rotor cores. The motor cost is calculated based on the cost estimation principles in text "Permanent Magnet Motor Technology" by J.F. Gieras[337] with the design spreadsheet in Appendix C. Heat sink calculations are included in Appendix A.

Bearings: In the magnetic bearing sub-component technology, four different magnetic bearing materials, based on magnetic load capability, density and power consumed were considered for the STMI FES system design. Permanent magnet capabilities are based on information from www.magnetsource.com[338]. The active magnetic bearing technology is a COTS capability available from Synchony[339].

1) Neodymium (NeFeB) permanent magnets, N-42 class, radial load capability (4.2 kg/cm^2), axial load capability (5.95 kg/cm^2), density (8400 kg/m^3) and power use (0 watts/cm).
2) Samarium Cobalt (Sa-Co) permanent magnets, 24 grade, radial load capability (2.4 kg/cm^2), axial load capability (3.40 kg/cm^2), density (7400 kg/m^3) and power use (0 watts/cm).
3) Ferrite Ceramic permanent magnets, class 5, radial load capability (0.34 kg/cm^2), axial load capability (0.48 kg/cm^2), density (4900 kg/m^3) and power use (0 watts/cm).
4) Active Electromagnets, radial load capability (5.1 kg/cm^2), axial load capability (3.24 kg/cm^2), density (3636 kg/m^3) and power use (9.26 watts/cm).

Based on a 4.5cm radius bearing rotor on the rotor shaft, a quick check of the magnetic bearing capability vs. required bearing length was done and recorded in Table 17 with the rotor masses listed in Table 16. Due to the length limits of the motor, ceramic magnets were eliminated as a potential technology based on over 80% of the predicted lengths being longer than the FES allowed length (max length minus rotor length).

The final technology dataset to be evaluated for the FES system design is included in Table 18 through Table 21 and has had the failed aluminum and steel rotor designs and the ferrite ceramic permanent magnets removed from analysis.

Table 17: Magnetic bearing capability length check

Rotor	Mass	Rotor shaft	NeFeB	SaCo	Ceramic	Active	Requirement 1.2 system length check with longest motor/generator length (0.98m) and vacuum enclosure bulk (0.15m)			
Designation	**(kg)**	**(m)**	**(m)**	**(m)**	**(m)**	**(m)**	**NeFeB**	**SaCo**	**Ceramic**	**Active**
Steel A514 (3-D)	4914	2.44	1.30	2.28	16.06	1.07	4.87	5.85	19.63	4.64
E-glass (S)	1597	1.39	0.42	0.74	5.22	0.35	2.94	3.26	7.74	2.87
E-glass (C&H)	1073	1.55	0.28	0.50	3.51	0.23	2.96	3.18	6.19	2.91
E-glass (3-D)	668	1.32	0.18	0.31	2.18	0.15	2.63	2.76	4.63	2.60
S-glass (S)	863	0.893	0.23	0.40	2.82	0.19	2.25	2.42	4.84	2.21
S-glass (C&H)	602	1.03	0.16	0.28	1.97	0.13	2.32	2.44	4.13	2.29
S-glass (3-D)	426	0.819	0.11	0.20	1.39	0.09	2.06	2.15	3.34	2.04
AS4C (S)	703	0.953	0.19	0.33	2.30	0.15	2.27	2.41	4.38	2.24
AS4C (C&H)	484	1.09	0.13	0.22	1.58	0.11	2.35	2.44	3.80	2.33
AS4C (3-D)	358	0.823	0.09	0.17	1.17	0.08	2.05	2.12	3.12	2.03
IM10 (S)	465	0.697	0.12	0.22	1.52	0.10	1.95	2.04	3.35	1.93
IM10 (C&H)	323	0.794	0.09	0.15	1.06	0.07	2.01	2.07	2.98	1.99
IM10 (3-D)	273	0.553	0.07	0.13	0.89	0.06	1.76	1.81	2.58	1.74
CNT (S)	313	0.562	0.08	0.14	1.02	0.07	1.77	1.84	2.71	1.76
CNT (C&H)	213	0.623	0.06	0.10	0.70	0.05	1.81	1.85	2.45	1.80
CNT (3-D)	215	0.383	0.06	0.10	0.70	0.05	1.57	1.61	2.22	1.56

S = Solid Rotor, C&H = Hollow Cylinder & Hub, & 3-D = Advanced 3-D rotor.
1.2 length requirements check (max 2.7m): Green = accepted, Red = failed

Table 18: FES database - rotor specifications

		Database entry	TRL ranking	Mass (kg)	Length (m)	Rotor design speed (rpm)	Complexity factor	Material Cost ($/kg)	Unit cost ($)	Development cost ($)	Development schedule (months)	Operations cost ($/yr.)	Maintenance cost ($/yr.)	Recycling /Disposal cost ($/kg)
Rotor materials and design	1	Steel (3-D)	5	4914	2.44	5600	4	$1.80	$17,170	$1,738,280	16.38	$600	$600	-$2,211
	2	E-glass (S)	7	1597	1.39	17250	1	$2.70	$6,376	$595,970	4.96	$600	$150	$1,078
	3	E-glass (C&H)	5	1073	1.55	16500	2.5	$2.70	$7,757	$1,421,460	13.21	$600	$375	$724
	4	E-glass (3-D)	4	668	1.32	16500	4	$2.70	$9,472	$2,066,700	19.67	$600	$600	$451
	5	S-glass (S)	7	863	0.893	23500	1	$16.00	$15,223	$588,630	4.89	$600	$150	$3,452
	6	S-glass (C&H)	5	602	1.03	22000	2.5	$16.00	$14,043	$1,412,040	13.12	$600	$375	$2,408
	7	S-glass (3-D)	4	426	0.819	22000	4	$16.00	$14,176	$2,060,650	19.61	$600	$600	$1,704
	8	AS4C (S)	7	703	0.953	26000	1	$23.00	$17,428	$587,030	4.87	$600	$150	$4,042
	9	AS4C (C&H)	5	484	1.09	24500	2.5	$23.00	$15,440	$1,409,680	13.10	$600	$375	$2,783
	10	AS4C (3-D)	4	358	0.823	24500	4	$23.00	$15,507	$2,058,950	19.59	$600	$600	$2,059
	11	IM10 (S)	7	465	0.697	32000	1	$64.00	$30,282	$584,650	4.85	$600	$150	$7,440
	12	IM10 (C&H)	5	323	0.794	30000	2.5	$64.00	$24,465	$1,406,460	13.06	$600	$375	$5,168
	13	IM10 (3-D)	4	273	0.553	30000	4	$64.00	$24,263	$2,056,825	19.57	$600	$600	$4,368
	14	CNT (S)	5	313	0.562	39000	1.5	$200.00	$62,394	$1,246,260	11.46	$600	$225	$15,650
	15	CNT (C&H)	4	213	0.623	37000	3	$200.00	$46,221	$1,855,325	17.55	$600	$450	$10,650
	16	CNT (3-D)	3	215	0.383	36500	4.5	$200.00	$49,451	$2,586,450	24.86	$600	$675	$10,750
	Shaft radius (m) = 0.03			Rotor radius (m) = 0.45			Rotor efficiency (%) = 98%			S = Solid Rotor, C&H = Hollow Cylinder & Hub, & 3-D = Advanced 3-D rotor				

Table 19: FES database – bearing specifications

		Database entry	TRL ranking	Density (kg/m^3)	load capacity (kg/cm^2)	load capacity (kg/cm^2)	Power use (watts/cm)	Complexity factor	Unit Cost + install ($/kg)	Development cost ($/kg)	Operations cost ($/yr./cm)	Maintenance cost ($/yr.)	Recycling /Disposal cost ($/kg)
Bearings	1	NeFeB PM N42 grade	7	8400	4.2	5.95	0	1.5	$235	$941	$0	$0	-0.30
	2	Sa-Co PM 24 grade	7	7400	2.4	3.4	0	1.5	$235	$941	$0	$0	-0.30
	3	Active Magnets (COTS)	8	3636	5.1	3.24	9.26	4	$627	$1,254	$12	$75	-0.20

Table 20: FES database – motor/generator specifications

		Database entry	TRL ranking	Total mass (kg)	Efficiency (%)	Length (m)	Power use (watts)	Complexity factor	Unit Cost ($)	Development Cost ($)	Development schedule (months)	Operations cost ($/yr.)	Maintenance cost ($/yr.)	Recycling /Disposal cost ($/kg)
Motor/Generator + cooling	1	93% + passive	7	1,083	93.0%	0.930	150	1	$13,063	$822,538	7.23	$1,092	$150	-$3,919
	2	93% + active	7	889	93.0%	0.930	235	1.1	$11,293	$751,706	6.52	$1,291	$165	-$3,388
	3	93% + active + TEG	6	890	93.0%	0.930	0	1.2	$11,388	$1,133,259	10.33	$1,080	$180	-$3,416
	4	95% + passive	6	974	95.0%	0.960	150	1.2	$13,442	$1,256,493	11.56	$1,272	$180	-$4,032
	5	95% + active	6	813	95.0%	0.960	235	1.3	$11,993	$1,169,568	10.70	$1,471	$195	-$3,598
	6	95% + active + TEG	5	814	95.0%	0.960	0	1.4	$12,088	$1,567,024	14.67	$1,260	$210	-$3,626
	7	96% + passive	5	922	96.0%	0.950	150	1.4	$14,360	$1,748,816	16.49	$1,452	$210	-$4,308
	8	96% + active	5	795	96.0%	0.950	235	1.5	$13,230	$1,658,376	15.58	$1,651	$225	-$3,969
	9	96% + active + TEG	4	796	96.0%	0.950	0	1.6	$13,325	$2,082,470	19.82	$1,440	$240	-$3,997
	10	97.5% + passive	4	862	97.5%	0.935	150	1.5	$15,743	$2,324,340	22.24	$1,542	$225	-$4,723
	11	97.5% + active	4	769	97.5%	0.935	235	1.6	$14,936	$2,243,590	21.44	$1,741	$240	-$4,481
	12	97.5% + active + TEG	3	770	97.5%	0.935	0	1.7	$15,031	$2,703,708	26.04	$1,530	$255	-$4,509

Table 21: FES database – vacuum enclosure specifications

		Database entry	TRL ranking	Air density (kg/m^3)	Cm constant	Material density (kg/m^3)	Material cost ($/kg)	Power use (watts)	Enclosure thickness (m)	Complexity factor	Vacuum pump mass (kg)	Vacuum pump cost ($)	Operations cost ($/yr.)	Maintenance cost ($/yr.)	Recycling /Disposal cost ($/kg)
Vacuum	1	Pumped enclosure, medium vacuum (1 Torr) with e-glass composite enclosure	7	0.002	0.027	2,120	2.70	120	0.01	1	9.5	$2,685	$16	$150	0.25
	2	Sealed enclosure, high vacuum (0.001 Torr) with e-glass composite enclosure	7	2E-06	0.0007	2,120	2.70	0	0.015	2	0	$0	$0	$0	0.25

Parametric values assigned within the database, especially for the bearing and vacuum enclosure designs, are the FES STMI team's best SME estimates and details are included in in Appendix D. Estimates for the development funding execution profile are based on current company manning and can change based on personnel hiring or reassignment.

4.3.2 STMI stage 2: Objective function operations and VE optimization

The initial design options for the 50KW-hr FES revolve around rotor design (16 options), vacuum enclosure design (2 options), bearing materials (3 options), and electric motor/generator (12 options) listed in Table 18 through Table 21 with a total of 1152 potential designs in a four dimensional design matrix. The FES components interact with each other through component mass, length and power usage and are illustrated in Figure 32 FES functional diagram.

During the Microsoft Excel spreadsheet "all case" analysis capability build, special care had to be given to track technology component interactions. The main advantage of the spreadsheet analysis methodology was to be able to visually inspect the analysis progress. The main disadvantage of utilizing an Excel spreadsheet on an AMD Athlon-II x4 processor personal computer with 4.0 GB RAM, was that the large STMI design spreadsheet started lagging as it ran out of allocated resources.

The STMI VE BV analysis performed exceptionally well, providing a rigorous and repeatable process which generated 407 successful FES designs out of 1152 potential design combinations, based on the documented customer requirements and constraints listed in Table 11and Table 14. Table 22 provides a summary of the top ten designs, and the analysis spreadsheet is provided in Appendix E as a reference. The BV FES system design, FES(11,5,1,2), incorporated the simpler rotor design with higher-end IM10 composites (#11), a moderately efficient motor/generator (#5), permanent magnetic lift bearings with an active axial magnet bearing (#1), and the sealed vacuum enclosure (#2). The BV design indicated that the FES design did not need all of the "best or "most complex" technologies to meet the customer requirement expectations.

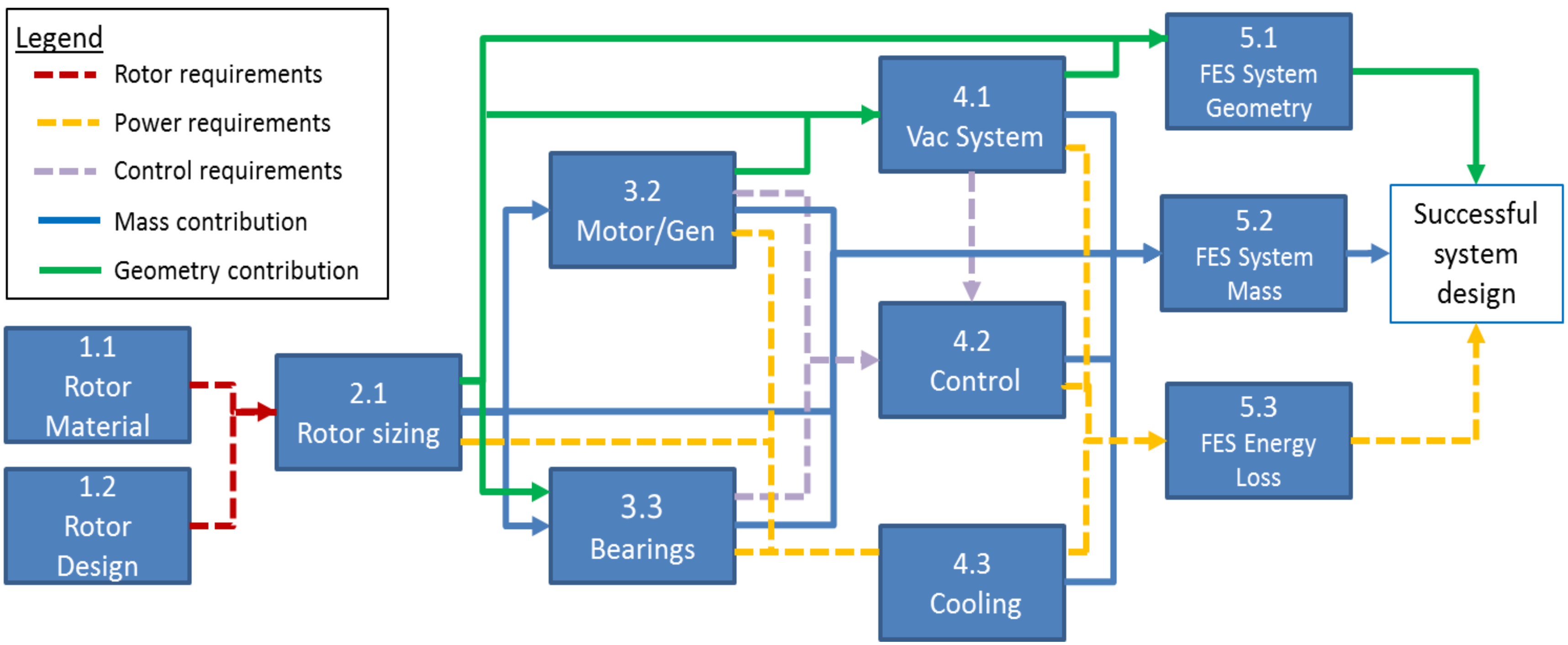


Figure 32: FES system objective function operation

Table 22: Top ten FES designs from STMI "best value" optimization +STP input

All cases analysis					Constraints										MinWorth	Best Value
					1600.0	2.7	85%	80000	10000000	10000000	100000	10000000	1000000		$1,939,384	0.9920
	Technology Number				Mass	Length	Effeciency	System Unit	Development	20 yr Ops	20 yr Ops	20 yr Maint.	Recycling/	Successful		
Run #	Rotor	Motor/Gen	Bearings	Vac.	(kg)	(m)	(%)	cost ($)	cost ($)	cost ($)	cost+eff.	cost ($)	disposal cost ($)	design? (Y/N)	Worth ($)	Best Value
1	11	5	1	2	1583.5	1.966	87.2%	$57,369	$1,882,015	$41,424	$18,667	$5,400	-$8,357	Y	$1,939,384	0.9920
2	11	5	3	2	1558.6	1.952	86.7%	$68,870	$1,881,753	$48,422	$29,910	$6,900	-$8,348	Y	$1,950,622	0.9799
3	11	5	1	1	1566.6	1.966	86.8%	$59,279	$1,905,000	$41,744	$22,313	$8,400	-$8,382	Y	$1,964,279	0.9762
4	11	5	3	1	1541.8	1.952	86.4%	$70,788	$1,904,759	$48,743	$33,557	$9,900	-$8,371	Y	$1,975,547	0.9646
5	11	6	1	2	1584.6	1.966	88.0%	$57,465	$2,299,479	$37,200	$6,453	$5,700	-$8,386	Y	$2,356,944	0.8215
6	11	6	3	2	1559.7	1.952	87.5%	$68,966	$2,299,217	$44,199	$17,697	$7,200	-$8,376	Y	$2,368,182	0.8133
7	11	6	1	1	1567.7	1.966	87.6%	$59,375	$2,322,464	$37,520	$10,100	$8,700	-$8,410	Y	$2,381,838	0.8107
8	11	6	3	1	1542.9	1.952	87.2%	$70,883	$2,322,223	$44,519	$21,344	$10,200	-$8,400	Y	$2,393,106	0.8026
9	11	8	1	2	1562.8	1.956	89.2%	$58,582	$2,390,631	$45,024	$2,241	$6,000	-$8,729	Y	$2,449,213	0.7920
10	11	8	3	2	1537.9	1.942	88.7%	$70,082	$2,390,369	$52,022	$13,484	$7,500	-$8,719	Y	$2,460,451	0.7843

All cases analysis										2014 constant year dollars				
	Technology Number				Development Cost ($)					Development Schedule (months)				
Run #	Rotor	Motor/Gen	Bearings	Vac.	Rotor	Motor/Gen	Bearings	Vacuum	Structure	Rotor	Motor/Gen	Bearings	Vacuum	Structure
1	11	5	1	2	$584,650	$1,229,568	$46,169	$9,967	$11,661	4.85	11.30	1.00	1.00	1.00
2	11	5	3	2	$584,650	$1,229,568	$46,146	$9,912	$11,477	4.85	11.30	1.00	1.00	1.00
3	11	5	1	1	$584,650	$1,229,568	$46,169	$33,076	$11,536	4.85	11.30	1.00	1.00	1.00
4	11	5	3	1	$584,650	$1,229,568	$46,146	$33,042	$11,353	4.85	11.30	1.00	1.00	1.00
5	11	6	1	2	$584,650	$1,647,024	$46,169	$9,967	$11,669	4.85	15.47	1.00	1.00	1.00
6	11	6	3	2	$584,650	$1,647,024	$46,146	$9,912	$11,485	4.85	15.47	1.00	1.00	1.00
7	11	6	1	1	$584,650	$1,647,024	$46,169	$33,076	$11,544	4.85	15.47	1.00	1.00	1.00
8	11	6	3	1	$584,650	$1,647,024	$46,146	$33,042	$11,362	4.85	15.47	1.00	1.00	1.00
9	11	8	1	2	$584,650	$1,738,376	$46,169	$9,928	$11,508	4.85	16.38	1.00	1.00	1.00
10	11	8	3	2	$584,650	$1,738,376	$46,146	$9,873	$11,325	4.85	16.38	1.00	1.00	1.00

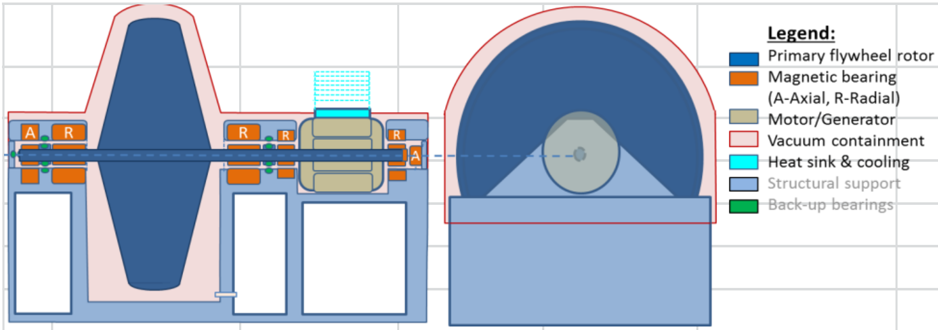
Identifying these technology options early in the system design allows for an optimized STP path. Taking the #1 FES BV system design development cost and schedule from Table 22, the PM can use these as inputs to build the recommended STP for the optimized FES system.

Allowing for six months of integration testing, the first operational FES prototype would be available in a 17.3 to 24.15 months timeframe, depending on funding and parallel development efforts. A sample STP option is presented in a traditional Gant chart type schedule illustrated in Figure 33. The technology maturation funding profiles would be integrated into the master budget and provide support for budget negotiations. Production and operational testing of the FES prototype would be dependent on capital funding and orders from utility companies, which is beyond the scope of the presented STMI process.

The STMI FES analysis spreadsheet was able to directly address the common problems previous PM teams had experienced when doing system designs. First, engineering design time required was reduced over 2000 man-hrs using the STMI FES analysis build (~12 hours) verses spending 1-2 hours manually for each of the 1152 system designs. Second, all of the technology options entered within the database were analyzed and examined with their mass, geometry and power interactions. Third, the specific technologies for the “Best Value” (BV) design were identified for development, providing a risk reduction path for technology maturation and system integration. Finally, the lifecycle costs and resources played a decisive role in the final BV system design. The spreadsheet was also set up to handle rapid trade studies and data sensitivity analysis inputs from the PM for post run analysis.

4.3.3 STMI stage 3: Post process FES system design analysis

Once the FES team proposed the formal FES design, the PM instructed them to conduct a series of rapid trade studies, sensitivity analysis and an incremental improvement analysis. The requirement trade studies were to focus on customer requirement changes that could impact the system designs. The sensitivity analysis was to examine the impacts of cost data uncertainty on the end optimization results.



Strategic Technology Plan

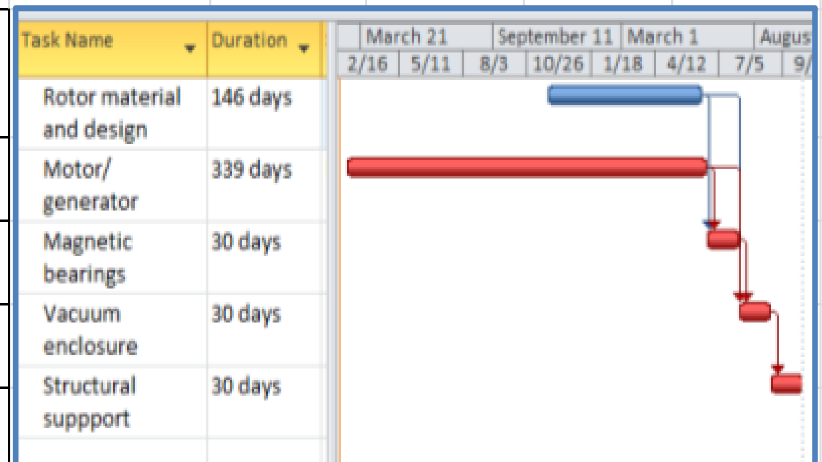
PM team proposed FES system design

Schedule time line: FY14-FY17

FY budgets	($M)
FY14	0.353
FY15	1.429
FY16	0.1

STMI BV optimized FES system design (11, 5, 1, 2)

	Technology component	Technology selection	Maturation cost ($K)	Maturation schedule (months)	Dependancies
1)	Rotor material and design	11	584.7	4.85	none
2)	Motor/ Generator	5	1229.6	11.3	none
3)	Bearings	1	46.2	1	1, 2
4)	Vacuum enclosure	2	10.0	1	1, 2, 3
5)	Structural support	default	11.7	1	4
		total	1882.0		



Red indicates critical path schedule

Figure 33: STMI “best value” FES design with Gant chart style inputs for a STP

The incremental improvement study was to examine significant changes in customer mass and length requirement thresholds to justify a new, compact system design delivery or “increment.”

4.3.3.1 Trade studies

After reviewing the design team’s FES recommendation, the PM requested trade studies to examine the trade space (changing requirements up and down slightly), and the adjustment of a few of the key input estimates that could change between formal design start and prototype production in three years. The PM also wanted the FES team to re-examine the ferrite ceramic magnetic bearings as a technology replacement for the Sa-Co magnets. The specific trade studies and goals are listed next.

Trade study #1: maximum FES mass variance +/- 10%

This trade study allowed the maximum FES system mass to vary an additional +/-10% of the lift capacity of the 2T fork lift (1500-1700 kg). The study’s purpose was to see if the number of successful FES design changed, if the top BV system changed from the baseline optimization, and if a lower system cost BV winner could be identified from the technology options.

Trade study #2: maximum FES system length variance +/- 10%

This trade study allowed the maximum FES system length to vary an additional +/-10% of the three times rotor diameter specification (2.43 - 2.97m). The study’s purpose was to see if the number of successful FES design changed, if the top BV system changed from the baseline optimization, and if a lower system cost BV winner could be identified from the technology options.

Trade study #3: FR compensation variance +/- $45,000

This trade study allowed the FR compensation to vary from the low of $175K to a high of $250k. The study’s purpose was to see if the changes in FR and the corresponding impact on operations costs for motor efficiency changed the number of successful FES designs, if the top BV system changed from the baseline optimization, and if a lower system cost BV winner could be identified from the technology options.

Trade study #4: Composite material price drop – 25% and -50%

This trade study allowed for the evolving prices of composite materials to drop after the three year FES development period. Current trends with automobile and aircraft manufacturers integrating high strength carbon composites into their vehicles are creating an increased demand and composite production capability, and carbon composite prices could see a 50% reduction in 3 years[340]. The study's purpose was to see if a 25% and the expected 50% change in composite prices changed the number of successful FES designs, if the top BV system changed from the baseline optimization, and if a lower system cost BV winner could be achieved for the production FES models in three years.

Trade study #5: replace Sa-Co with ferrite ceramic magnetic (FeCM) bearings

This trade study substituted the Samarium-Cobalt (Sa-Co) permanent magnets with the lower cost/lower density/lower power ferrite ceramic magnets. The study's purpose was to see if the number of successful FES design changed, if the top BV system changed from the baseline optimization, and if a lower system cost BV winner could be achieved.

Results from the trade studies are presented in Table 23 and are summarized below:

- Trade study #1, maximum FES mass variance +/- 10%:
    - Reducing the maximum FES mass yielded fewer successful designs (277 vs. 407). The top ten BV designs varied significantly from the baseline systems and relied on the higher complexity tech rotors utilizing higher tensile strength composite materials. The new BV designs required increased funding to build and develop over the baseline systems.
    - Increasing the maximum FES mass yielded 63 additional successful designs, but the FES(11,5,1,2) design remained top BV system.

Table 23: FES Trade study results

	Baseline study	Trade Study				
		1 (-10%/+10%)	**2 (-10%/+10%)**	**3 ($175K/$250K)**	**4 (-25%, -50%)**	**5 FeCM**
successful design #s	407	299 / 470	405 / 407	407 / 407	407 / 407	284
Top Ten FES designs	**Rotor, Motor/Generator, Bearing, Vacuum enclosure**					
#1	11,5,1,2	14,5,1,2 / 11,5,1,2	11,5,1,2 / same	11,5,1,2 / same	11,5,1,2 / same	11,5,1,2
#2	11,5,3,2	14,5,3,2 / 11,5,3,2	11,5,3,2 / same	11,5,3,2 / same	11,5,3,2 / same	11,5,3,2
#3	11,5,1,1	14,5,2,2 / 11,5,1,1	11,5,1,1 / same	11,5,1,1 / same	11,5,1,1 / same	11,5,1,1
#4	11,5,3,1	14,5,1,1 / 11,5,2,2	11,5,3,1 / same	11,5,3,1 / same	11,5,3,1 / same	11,5,3,1
#5	11,6,1,2	14,5,3,2 /11,5,3,1	11,6,1,2 / same	11,6,1,2 / same	11,6,1,2 / same	11,6,1,2
#6	11,6,3,2	14,5,2,2 /11,5,2,1	11,6,3,2 / same	11,6,3,2 / same	11,6,3,2 / same	11,6,3,2
#7	11,6,1,1	14,5,2,1 /11,6,1,2	11,6,1,1 / same	11,6,1,1 / same	11,6,1,1 / same	11,6,1,1
#8	11,6,3,1	12,5,2,1 /11,6,3,2	11,6,3,1 / same	11,6,3,1 / same	11,6,3,1 / same	11,6,3,1
#9	11,8,1,2	12,5,3,2 / 11,6,1,1	11,8,1,2 / same	11,8,1,2 / same	11,8,1,2 / same	11,8,1,2
#10	11,8,3,2	12,5,2,2 / 11,6,2,2	11,8,3,2 / same	11,8,3,2 / same	11,8,3,2 / same	11,8,3,2
#1 Best value score	0.9920	0.9956 / 0.9920	0.9920 / same	0.9899 / 0.9940	0.9914 / 0.9908	0.9920
Development cost ($K)	$1,882	$2,530 / $1,882	$1,882 / same	$1,882 / same	$1,882 / same	$1,882
Unit cost ($K)	$57.4	$86.5 / $57.4	$57.4 / same	$57.4 / same	$50.3 / $43.2	$57.4
Notes		(1)	(2)	(3)	(4)	(5)

- (1) lower mass requirements required higher tech rotors, (2) length change had minimal impact, (3) slightly shifted the BV score by increasing/ reducing the Operations cost with the lower/higher FR payment, (4) only lowers unit cost, (5) no change, Fe-ceramic magnets don’t even appear in the top 100 designs.

- Trade study #2, maximum FES system length variance +/- 10%:
  - Reducing the maximum FES system length yielded two fewer successful designs over the baseline analysis of 407. There was no change to the top BV FES system design compared with the baseline analysis.
  - Increasing the maximum FES system length yield no changes to the baseline number of successful designs, and no changes to the top baseline BV ranked FES system design.
- Trade study #3, FR compensation variance +/- $45,000:
  - Reducing the FR compensation made no changes to the top FES system list, but the BV scores decreased slightly due to the reduced FR credit being added to the operations cost.
  - Increasing the FR compensation made no changes to the top FES system, but the BV scores increased slightly due to the increased FR credit being added to the operations cost.
- Trade study #4, Composite material price drop – 25% and -50%:
  - Reducing the composite prices by either 25% or 50% did not change the top baseline BV ranked FES system design. What did change were a reduction in individual unit prices and a slight reduction in the BV scores.
- Trade study #5, replace Sa-Co with FeCM bearings:
  - Utilizing FeCM bearings instead of Sa-Co yielded a reduced number of successful FES designs (284 vs, 407). There were no change to the top baseline BV ranked FES system design, and the FeCM bearing designs did not have any units within the top 100 BV ranked FES systems designs.

Note: The trade studies required 10,368 additional design runs, which were completed in 1.5 man-hrs with the STMI FES analysis. This represents a consistent and rapid analysis capability with a significant time savings over completing the runs manually (~10,368 design team man-hrs).

4.3.3.2 Sensitivity analysis OVAT and DoE for cost estimates

A data sensitivity analysis was requested to examine system lifecycle cost variation by 20% to identify key components to watch for cost impacts in case initial cost estimation methods were incorrect. OVAT was recommended for examining all of the cost variables, and a DoE analysis was requested to determine if there is any significant interaction between the three OVAT variables that showed the highest potential for variability. The results from the 20% variation OVAT of the system cost components are shown in Table 24.

With the resulting ranges between the high BV and low BV response variables being less than 0.01, the analysis indicates that the overall BV scoring system for the top ranked FES designs were very insensitive to cost variation. So, once the BV scoring system found the recommended “best value” system, changes in the cost estimates created insignificant impacts to the final recommendations.

The #1 ranked BV system design and its corresponding technology set recommendation remained unchanged with the 20% cost variations. The operations cost had the largest variation range (0.00954) and therefore has the largest potential risk impact for cost changes on the BV solution.

The three highest cost variation scores from the OVAT analysis where selected (A=unit cost, B=development cost and C=operations cost) and placed into a three factor DoE analysis to determine factor interactions with the deterministic FES system design functions. The DoE analysis is shown in Table 25 and indicates that factor C has the highest impact to the BV calculations (same as OVAT), and that while minimal, the BxC interactions account for the largest multi-factor interaction.

Explanation note: a couple of the DoE BV scores were higher than the normalized 1.0. This is due to a bonus, described in section 4.3.1.1, where the motor/generator being examined is a higher effeciency than the 85% baseline and an effeciency credit was given, reducing the operations cost.

Table 24: STMI FES OVAT cost sensitivity analysis on BV score

	Sensitivity Analysis OVAT (BV Score)											
	Unit Cost Variance				Operations Cost Variance				Maintenance Cost Variance			
FES Successful System Design	Best (-20%)	Base	Worst (+20%)	Range	Best (-20%)	Base	Worst (+20%)	Range	Best (-20%)	Base	Worst (+20%)	Range
FES (11,5,1,2)	0.9919	0.9920	0.9920	0.00009	0.9962	0.9920	0.9878	0.00841	0.9925	0.9920	0.9914	0.00110
FES (11,5,3,2)	0.9810	0.9799	0.9789	0.00205	0.9848	0.9799	0.9752	0.00959	0.9806	0.9799	0.9793	0.00137
FES (11,5,1,1)	0.9763	0.9762	0.9762	0.00010	0.9803	0.9762	0.9721	0.00821	0.9771	0.9762	0.9754	0.00165
FES (11,5,3,1)	0.9657	0.9646	0.9635	0.00217	0.9693	0.9646	0.9599	0.00935	0.9655	0.9646	0.9636	0.00190
FES (11,6,1,2)	0.8207	0.8215	0.8224	0.00172	0.8241	0.8215	0.8189	0.00518	0.8219	0.8215	0.8211	0.00079
FES (11,6,3,2)	0.8132	0.8133	0.8134	0.00022	0.8163	0.8133	0.8103	0.00603	0.8137	0.8133	0.8128	0.00098
FES (11,6,1,1)	0.8099	0.8107	0.8115	0.00154	0.8133	0.8107	0.8082	0.00509	0.8113	0.8107	0.8101	0.00118
FES (11,6,3,1)	0.8026	0.8026	0.8027	0.00008	0.8056	0.8026	0.7997	0.00592	0.8033	0.8026	0.8020	0.00136
FES (11,8,1,2)	0.7911	0.7920	0.7929	0.00179	0.7949	0.7920	0.7891	0.00582	0.7924	0.7920	0.7916	0.00078
FES (11,8,3,2)	0.7841	0.7843	0.7845	0.00039	0.7876	0.7843	0.7810	0.00660	0.7848	0.7843	0.7838	0.00095

	Sensitivity Analysis OVAT (BV Score)							
	Development Cost Variance				Disposal Cost Variance			
FES Successful System Design	Best (-20%)	Base	Worst (+20%)	Range	Best (-20%)	Base	Worst (+20%)	Range
FES (11,5,1,2)	0.9900	0.9920	0.9933	0.00322	0.9911	0.9920	0.9928	0.00170
FES (11,5,3,2)	0.9752	0.9799	0.9832	0.00797	0.9791	0.9799	0.9808	0.00165
FES (11,5,1,1)	0.9734	0.9762	0.9781	0.00466	0.9754	0.9762	0.9771	0.00165
FES (11,5,3,1)	0.9591	0.9646	0.9683	0.00923	0.9638	0.9646	0.9654	0.00161
FES (11,6,1,2)	0.8223	0.8215	0.8210	0.00124	0.8209	0.8215	0.8221	0.00117
FES (11,6,3,2)	0.8120	0.8133	0.8141	0.00212	0.8127	0.8133	0.8138	0.00114
FES (11,6,1,1)	0.8108	0.8107	0.8106	0.00014	0.8101	0.8107	0.8113	0.00114
FES (11,6,3,1)	0.8008	0.8026	0.8039	0.00311	0.8021	0.8026	0.8032	0.00112
FES (11,8,1,2)	0.7931	0.7920	0.7912	0.00193	0.7914	0.7920	0.7926	0.00113
FES (11,8,3,2)	0.7836	0.7843	0.7848	0.00121	0.7838	0.7843	0.7849	0.00111

(green)	Baseline Best BV score
(cyan)	Sensitivity Analysis best range score
407	Baseline # of successful designs

Table 25: STMI FES DoE cost sensitivity analysis on BV score

Description

This template illustrates DOE or Design of Experiments sometimes called a Statistically Designed Experiment. A detailed discussion of DOE can be found at www.ASQ.org

Learn About Design of Experiments

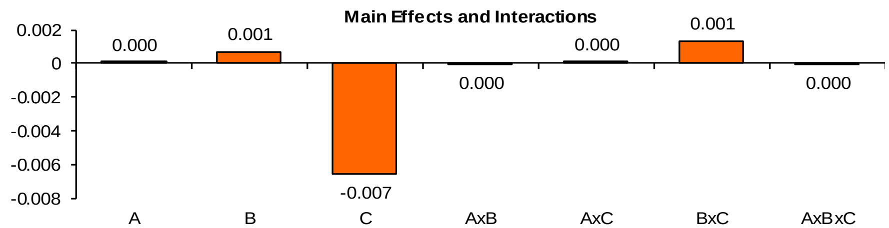
	Run Order	Unit cost	Dev. Cost	Ops Cost	AxB	AxC	BxC	AxBxC	Trial 1
1	6	67041	4383484	37794	1	1	1	-1	1.0019
2	8	67041	4383484	56691	1	-1	-1	1	0.9941
3	1	67041	6575226	37794	-1	1	-1	1	1.0013
4	4	67041	6575226	56691	-1	-1	1	-1	0.996
5	2	100562	4383484	37794	-1	-1	1	1	1.0019
6	5	100562	4383484	56691	-1	1	-1	-1	0.9942
7	3	100562	6575226	37794	1	-1	-1	-1	1.0013
8	7	100562	6575226	56691	1	1	1	1	0.9961

Instructions

- Enter the High and Low levels for factor A, B and C. Names and Levels are recommended but not required.

Factor Name	Factor Letter	Low Setting	High Setting
Unit cost	A	67041	100562
Dev. Cost	B	4383484	6575226
Ops Cost	C	37794	56691

- Run each of the eight combinations in random order using the Run Order Column.
- Collect at least one output measurement for each of the eight runs. Five are recommended.
- Review the bar graph to identify the factors or interactions having the greatest effect.
- If the effect of an interaction is shown to be large, use the interaction plots to determine the best settings that will optimize the output.
- Detailed calculations can be displayed by clicking on the radio button for any factor or interaction.



Select Factor or Interaction for Calculation Details:

○ A
○ B
○ C
○ A x B
○ A x C
◉ B x C
○ A x B x C

High (+1) settings: Effect:

average (1.0019 0.996 1.0019 0.9961) = 0.999 0.999

\- 0.9977

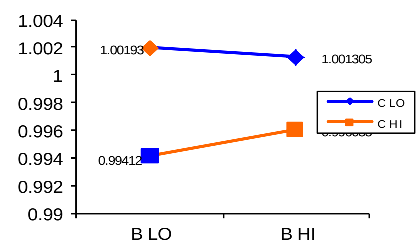
0.0013

Low (-1) settings:

average (0.9941 1.0013 0.9942 1.0013) = 0.9977

B x C Interaction

		C LO	C HI
B LO	1	1.0019	0.9941
	2	1.0019	0.9942
	Avg	1.0019	0.9941
B HI	1	1.0013	0.996
	2	1.0013	0.9961
	Avg	1.0013	0.996



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4.3.3.3 Incremental improvement FES design

An incremental improvement analysis for a future “advanced FES” design for potential emergency power and mobile applications was requested by the customer. The changed design requirements have a 25% mass and 25% length reduction over the current FES(11,5,1,2) design, plus a 87.5% efficiency rating. This new design technology maturation STP would be implemented in parallel with the original design STP. The customer also wants to know the tentative budget requirements and timeframe for the advanced prototype delivery.

After completing the STMI analysis runs, only four FES system designs were generated with the new system requirements:

1) FES(15,11,3,1), Dev. cost = $4,27M, unit cost = $80.5K, Dev. timeline = 43 months
2) FES(15,12,3,1), Dev. cost = $4.75M, unit cost = $80.6K, Dev. timeline = 48 months
3) FES(16,11,3,1), Dev. cost = $5.00M, unit cost = $83.7K, Dev. timeline = 50 months
4) FES(16,12,3,1), Dev. cost = $5.48M, unit cost = $83.8K, Dev. timeline = 55 months

The four “advanced FES” designs were under the 1200kg mass and two meter length requirement, but each depended on the advanced technologies in the CNT composite rotor design and ultra-high efficiency motor/generator. The new rotors were more expensive than the baseline design by $23,000-$26,300 each, and required nearly double the developmental funding ($4.27M vs $2.3M) with over 43 months of development schedule. If the “advanced FES(15,11,3,1)” system was fully funded and started development at the same time as the baseline FES(11,5,1,2) schedule in Figure 33, it would be ready for TR-6 prototype testing in ~1.5 years after the baseline system.

4.4 <u>Macro-level STMI FR system selection</u>

Now that the PM’s FES team has completed the micro FES BV analysis, it is time to apply the individual FES units to the FES 20MW utility plant and insert it into the Macro-FR STMI system analysis. Figure 34 illustrates the FES facility plan placement within a typical utility grid.

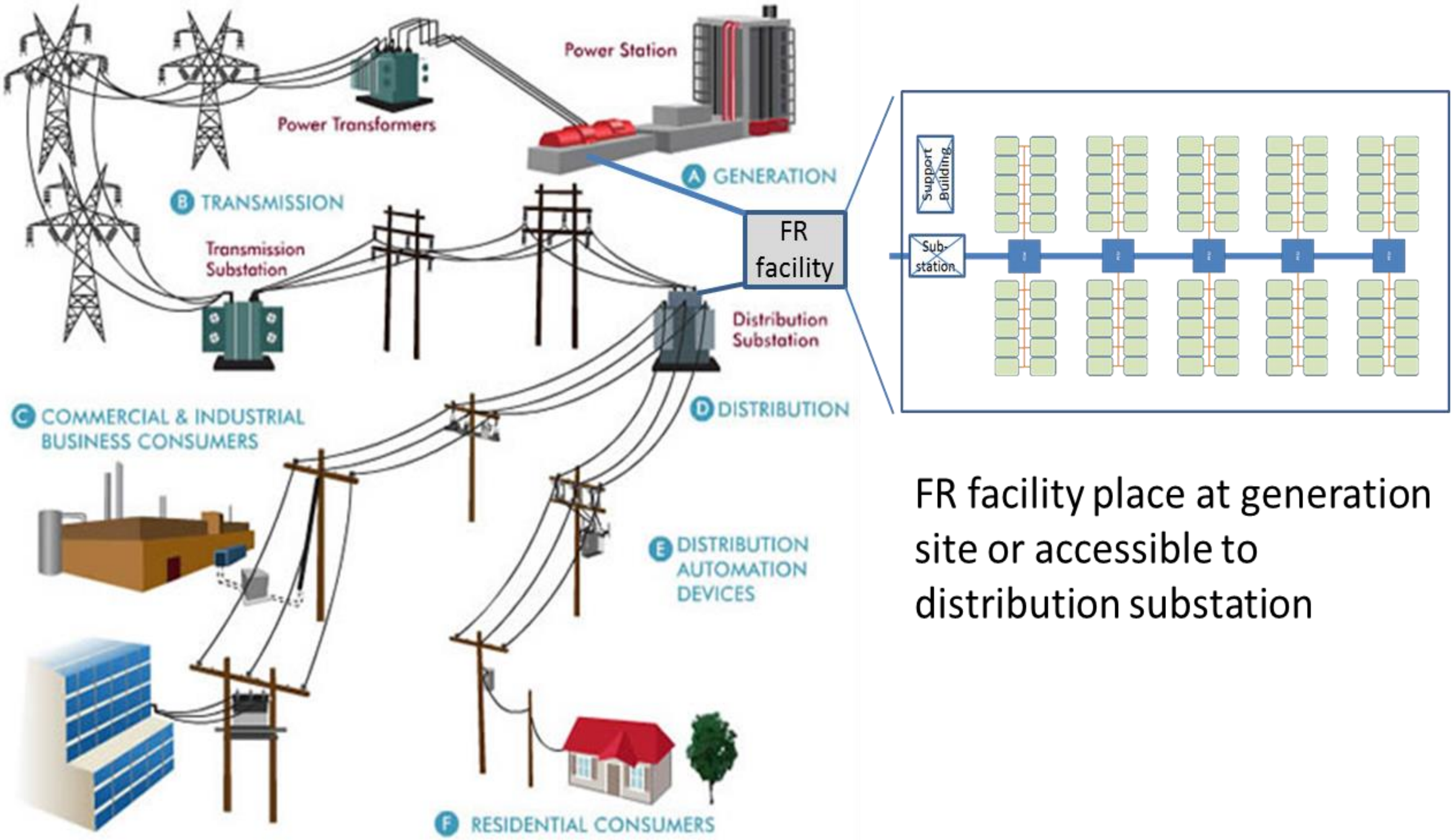

Figure 34: FR facility placement within the utility grid

The original FES FR facility overview in Figure 30b, contains 100 of the individual FES units to create a 20MW (5MWh) facility capable for 15 min of FR service operation. Twenty FES units are connected in parallel to a transformer which increased the FES 480v output to 13.8kV. The entire FES utility plant connects to the utility grid with a utility switchyard transformer, which increases the plant output voltage from 13.8kV to the standard grid 115-138kV transmission line voltage[341].

Using the 14.5 months of FES technology maturation to design and build the pilot plant to manufacture 100 FES units in a six month period, plus six months to conduct the install and Operational Test and Evaluation (OT&E), the first FES utility plant could be operational within 26.5 months from project initiation. This places the FES utility plant within the near-term (0-5yr) project window requested by the case study customers.

The components of the FES utility plant cost estimates include:

1. 100 individual FES(11,5,1,2) units with 480v, 200kW output
   - Development cost (TRL-6) = $1.88M
   - Maturation cost (TRL-9) = 4*($1.88M) + $5M = $12.52M (OT&E & pilot plant)
   - Units cost = 100*($57.4K) + 100*($26K G&A) + 100*($5K install) = $8.84M
   - 20 yr Maintenance cost = 100*($41.4K) = $4.14M
   - 20 yr Operations cost = 100*($18.7K) = $1.87M
   - Disposal/recycling cost = 100*(-$8.4K) = -$0.84M
2. 10, 480v to 13.8kV step-up transformers[342]
   - Development cost to link arrays= $2.8M
   - Units cost = 10*($100K/unit) + 10*($5K install/unit) = $1.05M
   - 20 yr Maintenance cost = 10*($1K)*20 = $0.2M
   - 20 yr Operations cost = 10*($1.5K)*20 = $0.3M
   - Disposal/recycling cost = 10*($25K) = $0.25M
3. Land next to distribution substation, security and monitoring facility
   - Development cost = $1.5M (includes permits and access fees)
   - Facility unit cost = $2.5M
   - Shipping & delivery unit costs = 100*($10K) + 10*($8K) = $1.08M

- 20 yr Maintenance cost = ($20K)*20 = $0.4M
- 20 yr Operations cost = ($25K)*20 = $0.5M
- Disposal/recycling/resale cost = -$1.0M

Total estimated costs associated with the FES utility plant:

- Development/maturation cost = $1.88M + $12.52M + $2.8M + $1.5M = <u>$18.7M</u>
- Facility unit build cost = $8.84M + $1.05M + $2.5M + $1.08M = <u>$13.47M</u>
- 20 yr Maintenance cost = $4.14M + $0.2M + $0.4M = <u>$4.74M</u>
- 20 yr Operations cost = $1.87M + $0.3M + $0.5M = <u>$2.67M</u>
- Disposal/recycling/resale cost = -$0.84M + $0.25M + -$1.0M = <u>-$1.59M</u>

The overall BV score for potential 20 MW FR systems is provided in Table 26. Other systems examined are taken from historical data, government parametrics and developed together for the FR application comparison.

The final results for the STMI Macro FR system selection indicates that the FES FR facility, with a BV score of 0.754, would be significantly competitive compared to all of the researched FR options. The FES FR facility requires a lower start-up costs and a moderately low development cost. The FES system's saving gain comes from the inherent, very low Operations and Maintenance (O&M) costs, making its lifecycle costs one of the lowest in the field of FR capabilities. When a PM is looking at technologies to invest technology R&D money into, a system with a high BV score compared to its peers will yield the lowest lifecycle cost and lower risk for failure once produced.

Table 26: Macro-level FR system design

FR System description (20 MW)	Development cost	Facility ramp rate in 5 min	Facility capitol cost	20 Year O&M cost	Disposal/ recycling cost	BV Score (overall minWorth / system cost)
STMI designed FES 100 units FR plant	$18.7M	100%	$13.47M	$7.41M	-$1.59M	0.754
Beacon Power FES[343,344,345] 200 units FR plant	$150M****	100%	$54M*****	$15M	-$6.2M	0.135
A123 Li-ion Batteries*[346,347]	$132M****	100%	$27.2M	$16.7M*	$2.720M	0.160
Xtreme Power Dry Cell Batteries*[348,349,350]	$29.5M****	100%	$24.2M	$10M*	$1.63M	0.438
Sodium-Sulfur Batteries*[351, 352, 353]	$7.9M****	100%	$21.75M	$13.32M*	$2.18M	0.634
Gas turbine power plant[354, 355]	$2.6M	100% (with two units)	$26.04M	$27.65M*	$3.3M***	0.481
Pumped Hydropower storage (PSH)[356]	$4.6M**	100%	$45.94M	$12.32M	$11.5M***	0.381
Compressed Air Energy Storage (CAES)[357, 358]	$54.5M****	100% (with two units)	$36M	$11.95M	$4.5M***	0.268
Overall minWorth = Gas Turbine Development + facility cost = $28.64M						
System Cost = Development cost+ Facility cost + O&M cost + disposal/recycling cost						

Systems are assumed to be gov/utility owned, so potential commercial earnings are not considered in the system design EV BV analysis.
Systems are sized to meet full power requirements at 5 min based on ramp-up rate (Gas turbine sources had two different rates, split difference)
Dry cell batteries O&M costs are 25% less than NaS batteries, Lithium-ion 25% more than NaS due to battery replacement costs
* Costs do not include CO2 fees or costs to recycle batteries. Battery systems are replaced every 50000hrs (~5.9 yrs).
** Assume that appropriate local geology is available; fees include plans, permits and surveys.
*** Assumed decommission at 25% of capitol build cost.
****Development funds are based on published DOE energy grant development fund usage
*****Two plants have been constructed for $62M and $46M. Average value used.

5 Conclusions and expected contributions

Strategic Technology Planning has been an active field of research in many areas within industrial and the DoD acquisition “lifecycle” timeline. Researchers, developers and program managers have expended enormous time and resources to study and develop methodologies to improve how technology is identified, matured and eventually inserted into a viable product or service. Despite a growing body of literature and government regulations, Strategic Technology Plan (STP) generation has primarily been a manual, subjective methodology conducted by subject matter experts.

The introduction of the STMI process to assist in building a STP offers to change this manual paradigm by providing a computer-based Decision Support System (DSS) tool. The STMI DSS research brings together a combination of previously unsynchronized tools to create a systematic, best value analysis process for decision makers evaluating technology options. This STMI DSS offers users a demonstrated method to:

- Evaluate system concepts with the best available combination of technologies, with a focus on technology maturation and lifecycle costs, that yield a best value system design for the customer
- Automate technology selections to help eliminate bias and utilize a common evaluation methodology across all system designs
- Account for secondary technology interactions within the system design
- Provide repeatable, analytical input for a Strategic Technology Plan designed to mature required technologies to a TRL-6 and prepare them for full system prototyping
- Make technology planning and maturation efforts more accurate and defendable given the inter-connected nature of customer requirements
- Allow rapid trade and incremental improvement studies to examine “what if” scenarios with changes to technology performance, customer requirements, maturation schedule and budgeted cost
- Assess data sensitivity impacts to the system design technology selections

6 Future research opportunities and ongoing work

Future research can be directed to develop and expand the presented STMI process for implementation in a true DSS software environment. These capabilities could include:

1) Linked graphical user interface and database management
2) Apply a metaheuristic (like Genetic Algorithm) to optimize run time vs. accuracy
3) Ranked listing of the user selected top number of BV system design solutions for review and trend analysis
4) Batch processing to conduct sensitivity analysis with OFAT or with multi-factor Designs of Experiments (DOE) analysis
5) Incorporate MS Excel "At Risk™" or similar method for adding stochastic variability into the STMI technology database to account for uncertainty in technology performance, cost and schedule

Ongoing work includes commercializing the STMI process methodology to provide potential customers with the early lifecycle analysis capability.

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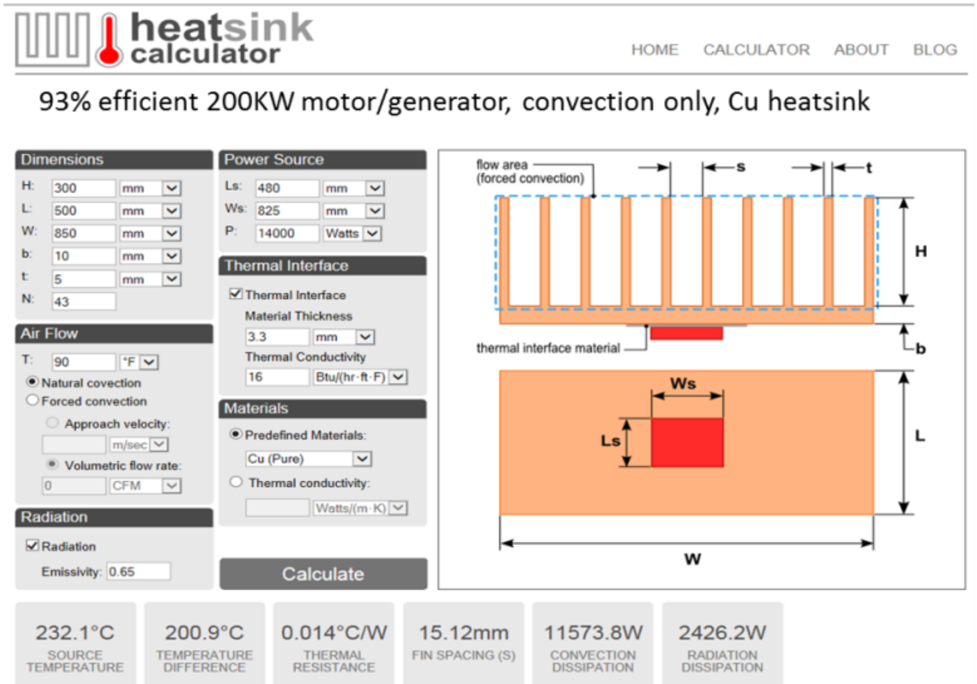
Appendices

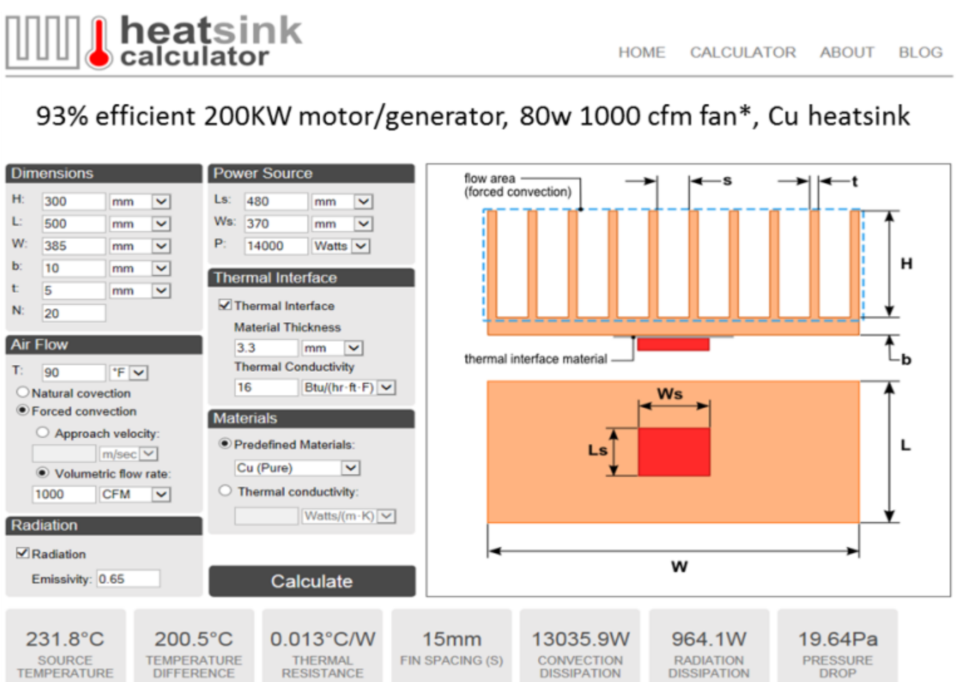
Appendix A: Heat sink design specifications



Temperature differential target =200°C to reduce internal material damage and external fire hazards and allow for high temperature thermal interface grease or Peltier TEG operation

Powersource + heatsink mass = $\rho\ (850N + 775 + 4.80w_s)$

copper $\rho\ = 0.008933$ kg/cm^3, Mass = 369kg @ \$10/kg for material and build price = \$3690

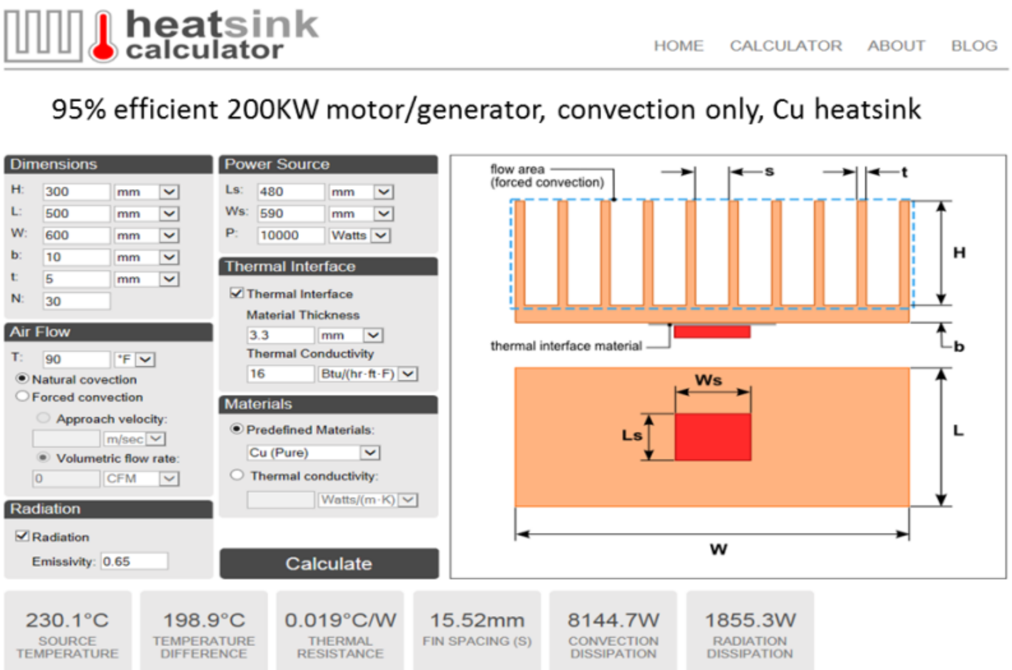


Temperature differential target =200°C to reduce internal material damage and external fire hazards and allow for high temperature thermal interface grease and/or Peltier TEG operation (add \$100 to cost)

* Four weather resistant, 120mm diameter, 12v fan @\$20 each, www.nmbtc.com

Powersource + heatsink mass = $\rho\ (850N + 775 + 4.80w_s)$

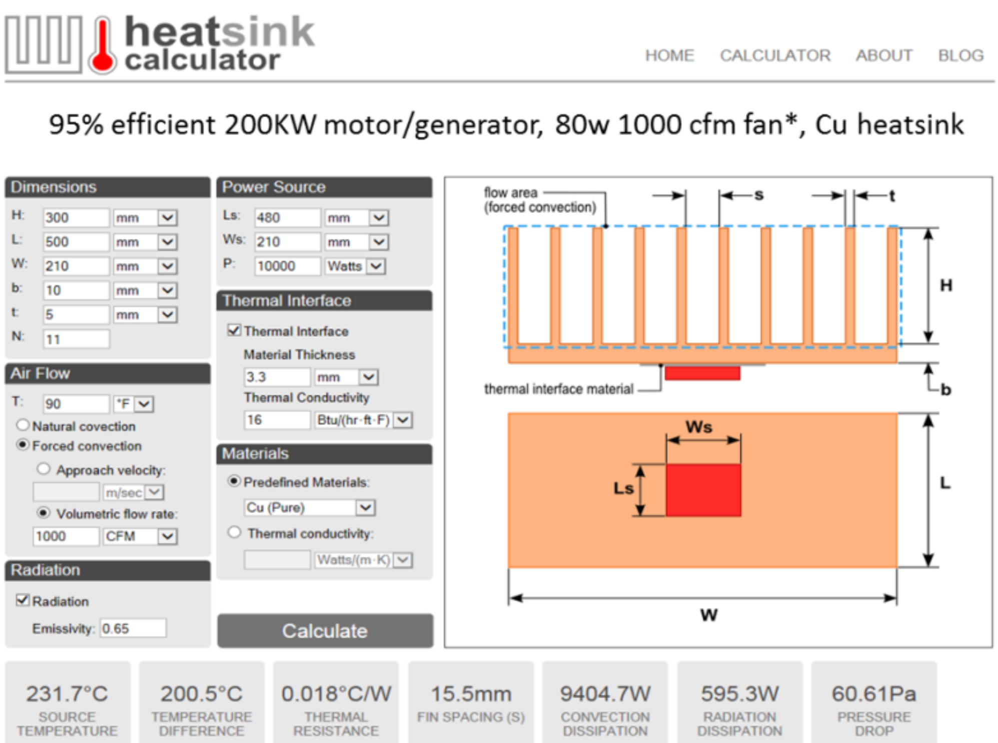
copper $\rho\ = 0.008933$ kg/cm^3, Mass = 175kg @ \$10/kg for material and build price + \$80 fans = \$1826



Temperature differential target =200°C to reduce internal material damage and external fire hazards and allow for high temperature thermal interface grease or Peltier TEG operation

Powersource + heatsink mass = $\rho\ (850N + 775 + 4.80w_s)$

copper ρ = 0.008933 kg/cm^3, Mass = 260kg @ \$10/kg for material and build price = \$2600



Temperature differential target =200°C to reduce internal material damage and external fire hazards and allow for high temperature thermal interface grease and/or Peltier TEG operation (add \$100 to cost)

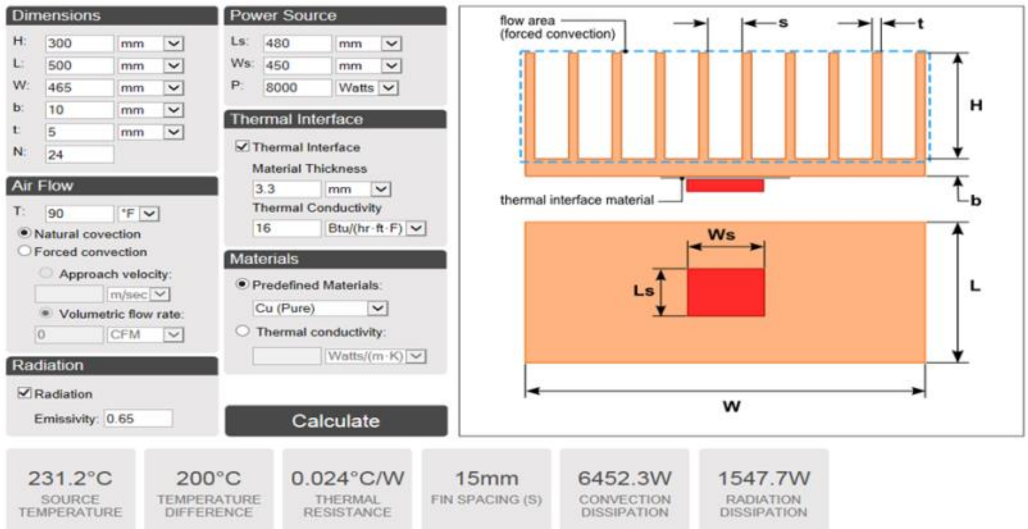
* Four weather resistant, 120mm diameter, 12v fan @\$20 each, www.nmbtc.com

Powersource + heatsink mass = $\rho\ (850N + 775 + 4.80w_s)$

copper ρ = 0.008933 kg/cm^3, Mass = 99.5kg @ \$10/kg for material and build price + \$80 fans = \$1075 heatsink calculator

HOME CALCULATOR ABOUT BLOG

96% efficient 200KW motor/generator, convection only, Cu heatsink



Temperature differential target =200°C to reduce internal material damage and external fire hazards and allow for high temperature thermal interface grease or Peltier TEG operation

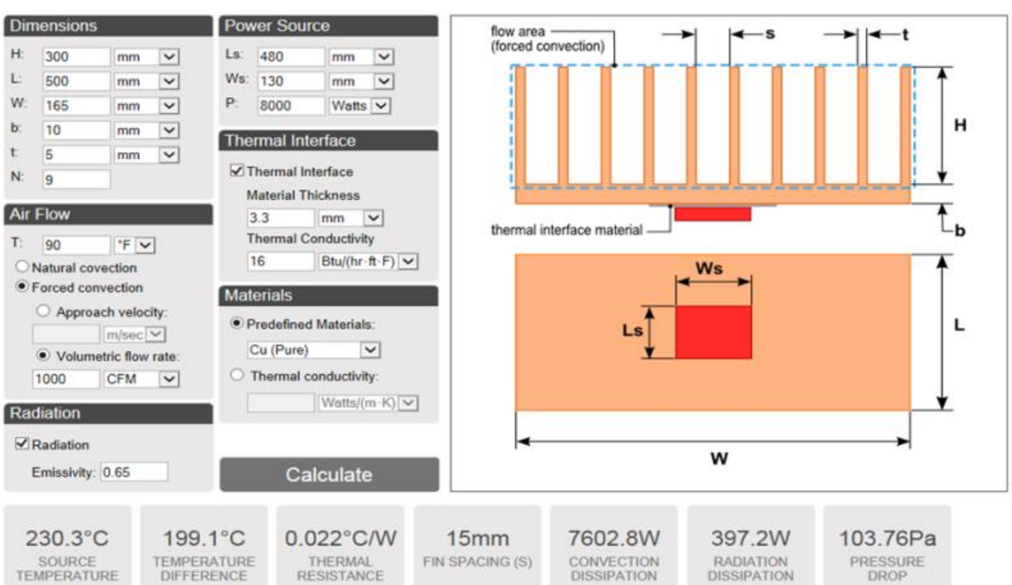
Powersource + heatsink mass = $\rho\ (850N + 775 + 4.80w_s)$

copper $\rho = 0.008933$ kg/cm^3, Mass = 208kg @ $10/kg for material and build price = $2080

heatsink calculator

HOME CALCULATOR ABOUT BLOG

96% efficient 200KW motor/generator, 80w 1000 cfm fan*, Cu heatsink



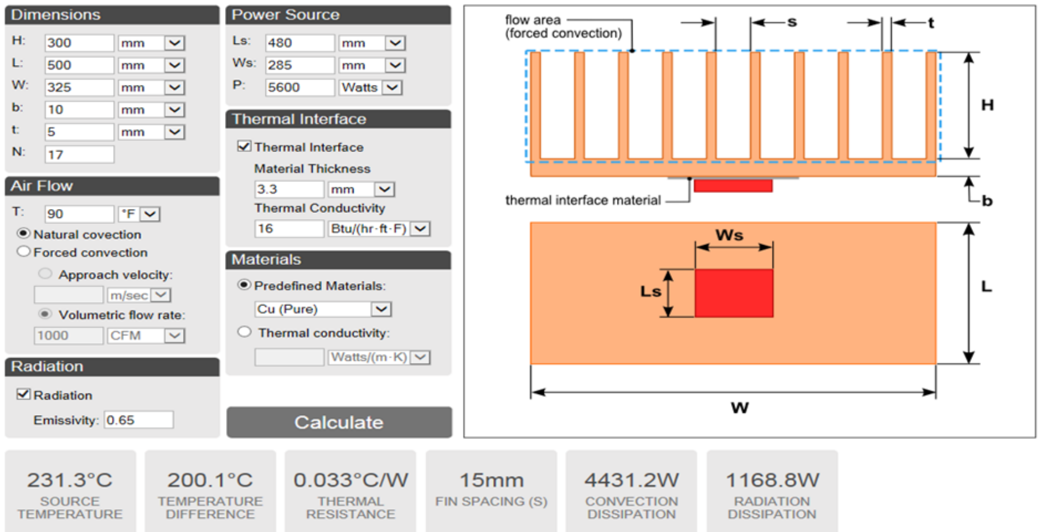
Temperature differential target =200°C to reduce internal material damage and external fire hazards and allow for high temperature thermal interface grease and/or Peltier TEG operation (add $100 to cost)

* Four weather resistant, 120mm diameter, 12v fan @$20 each, www.nmbtc.com

Powersource + heatsink mass = $\rho\ (850N + 775 + 4.80w_s)$

copper $\rho = 0.008933$ kg/cm^3, Mass = 81kg @ $10/kg for material and build price + $80 fans = $890 heatsink calculator HOME CALCULATOR ABOUT BLOG

97.5% efficient 200KW motor/generator, convection only, Cu heatsink



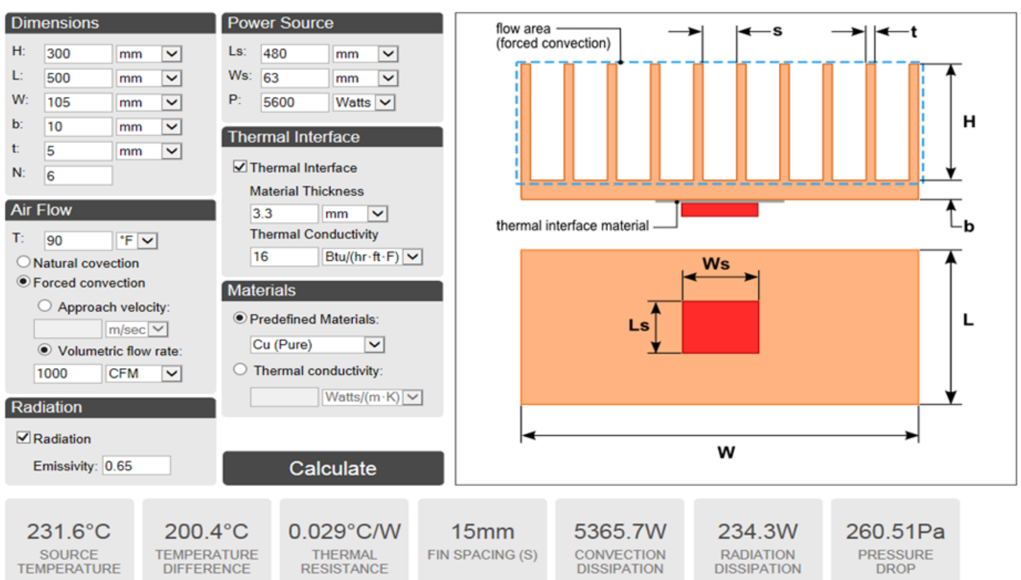
Temperature differential target =200°C to reduce internal material damage and external fire hazards and allow for high temperature thermal interface grease or Peltier TEG operation

Powersource + heatsink mass = $\rho\ (850N + 775 + 4.80w_s)$

copper $\rho\ = 0.008933$ kg/cm^3, Mass = 148kg @ \$10/kg for material and build price = \$1480

heatsink calculator HOME CALCULATOR ABOUT BLOG

97.5% efficient 200KW motor/generator, 80w 1000 cfm fan*, Cu heatsink



Temperature differential target =200°C to reduce internal material damage and external fire hazards and allow for high temperature thermal interface grease and/or Peltier TEG operation (add \$100 to cost)

* Four weather resistant, 120mm diameter, 12v fan @\$20 each, www.nmbtc.com

Powersource + heatsink mass = $\rho\ (850N + 775 + 4.80w_s)$

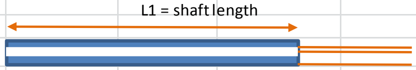
copper $\rho\ = 0.008933$ kg/cm^3, Mass = 55kg @ \$10/kg for material and build price + \$80 fans = \$630

Appendix B: FES rotor designs

Solid cylinder rotor design with Aluminum 2014-T6 alloy

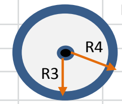
Pi =	3.141592654
~1.4 safety factor	
~1.25 safety factor	

L1 = shaft length



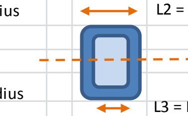
R1 = inner shaft radius
R2 = outer shaft radius

R3 = Cycinder Inner Radius



R4 = Cycinder Outer Radius

L2 = Cyclinder length



L3 = Hub length

Shaft Specifications

0.33	Poisson's Ratio
2800	Shaft material density
414	Shaft material (MPa)
Al	Shaft Material Description

Hub Specifications

0.33	Poisson's Ratio
2800	Hub & disk material density kg/m^3
414	Hub & disk MPa tensile strength
Al	Hub & Disk Material Description

Rim Specifications

0.33	Poisson's Ratio
2800	Rim material density (kg/m^3)
414	Rim MPa tensile strength (MPa)
Al	Hub & Disk Material Description

Design Specifications

0.4	Rim K factor
0	Hub disk K factor
0.5	Shaft K factor
0.98	Storage effeciency

Flywheel Specs

5.0778	Shaft length, l1 (m)
0.03	Shaft radius, R2 (m)
0	Shaft inner radius, R1 (m)
40.20	Shaft mass (kg)
0.018	Shaft Inertia (kg-m^2)
Rev step	200

0.0000	Hub-Disk Length, L3 (m)
0.0000	Hub-Disk volume (m^3)
0.00	Hub-Disk mass (kg)
2800.00	Hub-disk effective Density (kg/m^3)
0.000	Hub-Disk Inertia (kg-m^2)

8650.00	Rim cylinder mass (kg)
0.0668	Cylinder inner diameter (% of radius)
3.0893	Rim structure volume (m^3)
879.7205856	Rim Cylinder Inertia (kg-m^2)
0.03006	Cylinder inner diameter, R3 (m)

50	Energy storage target kWh
0.4500	Rotor Rim Outer Radius, R4 (m)
4.8778	Rotor Rim Cylinder Height, L2 (m)
8690.20	Total Rotor + shaft Mass (kg)
5.75	Watts-hr/kg estimate
0.016113	kWh/liter estimate

Rotor rev/min	Stored Energy (shaft) (kWh)	Stored Energy (Hub) (kWh)	Stored Energy (Cylinder) (kWh)	Total Energy Stored (kWh)	Shaft Hoop or radial Stress est. (Mpa)	Cylinder Radial Stress (MPa)	Cylinder Hoop Stress (MPa)	Hub-Disk Radial Stress (Mpa)	Hub-Disk Hoop Stress (Mpa)
5000	0.00068	0.00000	26.26187	26.263	0.30	67.56	135.81	0.00	0.69
5200	0.00073	0.00000	28.40483	28.406	0.33	73.07	146.90	0.00	0.75
5400	0.00079	0.00000	30.63184	30.633	0.35	78.80	158.41	0.00	0.81
5600	0.00085	0.00000	32.94288	32.944	0.38	84.75	170.36	0.00	0.87
5800	0.00091	0.00000	35.33797	35.339	0.41	90.91	182.75	0.00	0.93
6000	0.00097	0.00000	37.81709	37.818	0.43	97.29	195.57	0.00	1.00
6200	0.00104	0.00000	40.38024	40.381	0.46	103.88	208.83	0.00	1.07
6400	0.00111	0.00000	43.02744	43.029	0.49	110.69	222.52	0.00	1.14
6600	0.00118	0.00000	45.75867	45.760	0.53	117.72	236.64	0.00	1.21
6800	0.00125	0.00000	48.57395	48.575	0.56	124.96	251.20	0.00	1.28
7000	0.00132	0.00000	51.47326	51.475	0.59	132.42	266.19	0.00	1.36
7200	0.00140	0.00000	54.45660	54.458	0.63	140.09	281.62	0.00	1.44
7400	**0.00148**	**0.00000**	**57.52399**	**57.525**	**0.66**	**147.98**	**297.49**	**0.00**	**1.52**
7600	0.00156	0.00000	60.67541	60.677	0.70	156.09	313.78	0.00	1.60
7800	0.00164	0.00000	63.91087	63.913	0.73	164.41	330.52	0.00	1.69
8000	0.00173	0.00000	67.23037	67.232	0.77	172.95	347.68	0.00	1.77
8200	0.00182	0.00000	70.63391	70.636	0.81	181.71	365.28	0.00	1.86
8400	0.00191	0.00000	74.12149	74.123	0.85	190.68	383.32	0.00	1.96
8600	0.00200	0.00000	77.69310	77.695	0.89	199.87	401.79	0.00	2.05
8800	0.00209	0.00000	81.34875	81.351	0.93	209.27	420.70	0.00	2.15
9000	0.00219	0.00000	85.08844	85.091	0.98	218.89	440.04	0.00	2.25
9200	0.00229	0.00000	88.91217	88.914	1.02	228.73	459.81	0.00	2.35
9400	0.00239	0.00000	92.81994	92.822	1.07	238.78	480.02	0.00	2.45

Kinetic Energy Storage: E = K*I*ω^2
where (ω^2) = (w*2*Pi/60)^2)

Shaft Inertia (thick cylinder): I_{shaft} = 0.5*m*(R1^2 +R2^2)

Hub-disk Inertia (thick cylinder): I_{hub} = 0.5*m*(R2^2 +R3^2)

Solid Cylinder Radial Stress: $\sigma_{r\_max} = \sigma_{t\_max} = \rho\omega^2(3-2\upsilon)/8(1-\upsilon)R_4^2$

Hollow Cylinder Radial Stress: $\sigma_{r\_max} = (\rho\omega^2(3-2\upsilon)/8(1-\upsilon))*(R_4^2 - R_3^2)$

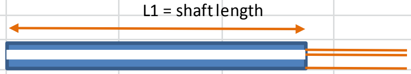
Hollow Cylinder Hoop Stress: $\sigma_{t\_max} = \rho\omega^2/4(1-\upsilon)\,[(1-2\upsilon)R_3^2 + (3-2\upsilon)R_4^2]$

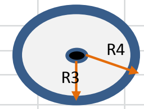
Target Design is >=15% over KWh requirement with 40% safety factor for metal rotors and 25% safety actord for composite rotors

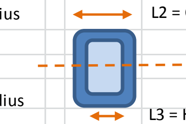
Assume K=0.4 for the solid cylinder flywheel due to radial composit wrap not optimal for radial stress.

Hollow cylinder + hub rotor design with Aluminum 2014-T6 alloy

Pi =	3.141592654
~1.4 safety factor	
~1.25 safety factor	







Shaft Specifications		Hub Specifications		Rim Specifications		Design Specifications	
0.33	Poisson's Ratio	0.33	Poisson's Ratio	0.33	Poisson's Ratio	0.5	Rim K factor
2800	Shaft material density	2800	Hub & disk material density kg/m^3	2800	Rim material density (kg/m^3)	0.5	Hub disk K factor
414	Shaft material (MPa)	414	Hub & disk MPa tensile strength	414	Rim MPa tensile strength (MPa)	0.5	Shaft K factor
Al	Shaft Material Description	Al	Hub & Disk Material Description	Al	Hub & Disk Material Description	0.98	Storage effeciency

Flywheel Specs							
5.5637	Shaft length, l1 (m)	1.4400	Hub-Disk Length, L3 (m)	4180.00	Rim cylinder mass (kg)	50	Energy storage target kWh
0.03	Shaft radius, R2 (m)	0.5112	Hub-Disk volume (m^3)	0.7500	Cylinder inner diameter (% of radius)	0.4500	Rotor Rim Outer Radius, R4 (m)
0	Shaft inner radius, R1 (m)	1431.44	Hub-Disk mass (kg)	1.4929	Rim structure volume (m^3)	5.3637	Rotor Rim Cylinder length L2 (m)
44.05	Shaft mass (kg)	10976.39	Hub-disk effective Density (kg/m^3)	661.2890625	Rim Cylinder Inertia (kg-m^2)	5655.49	Total Rotor + shaft Mass (kg)
0.020	Shaft Inertia (kg-m^2)	82.169	Hub-Disk Inertia (kg-m^2)	0.3375	Cylinder inner diameter, R3 (m)	8.84	Watts-hr/kg estimate
Rev step	200					0.014653	kWh/liter estimate

Rotor rev/min	Stored Energy (shaft) (kWh)	Stored Energy (Hub) (kWh)	Stored Energy (Cylinder) (kWh)	Total Energy Stored (kWh)	Shaft Hoop or radial Stress (Mpa)	Cylinder Radial Stress (MPa)	Cylinder Hoop Stress (MPa)	Hub-Disk Radial Stress (Mpa)	Hub-Disk Hoop Stress (Mpa)
5000	0.00074	3.06619	24.67642	27.743	1.18	29.69	146.82	148.46	11.70
5200	0.00080	3.31639	26.69002	30.007	1.28	32.11	158.80	160.57	12.65
5400	0.00086	3.57641	28.78258	32.360	1.38	34.63	171.25	173.16	13.64
5600	0.00093	3.84623	30.95410	34.801	1.48	37.24	184.17	186.23	14.67
5800	0.00100	4.12587	33.20459	37.331	1.59	39.95	197.56	199.77	15.74
6000	0.00107	4.41532	35.53405	39.950	1.70	42.75	211.42	213.78	16.84
6200	0.00114	4.71458	37.94246	42.658	1.82	45.65	225.75	228.27	17.98
6400	0.00121	5.02365	40.42985	45.455	1.94	48.64	240.55	243.24	19.16
6600	0.00129	5.34253	42.99620	48.340	2.06	51.73	255.82	258.68	20.38
6800	0.00137	5.67123	45.64151	51.314	2.19	54.91	271.56	274.59	21.63
7000	0.00145	6.00973	48.36578	54.377	2.32	58.19	287.76	290.98	22.92
7200	**0.00153**	**6.35805**	**51.16903**	**57.529**	**2.45**	**61.57**	**304.44**	**307.85**	**24.25**
7400	0.00162	6.71618	54.05123	60.769	2.59	65.03	321.59	325.19	25.62
7600	0.00171	7.08413	57.01240	64.098	2.73	68.60	339.21	343.00	27.02
7800	0.00180	7.46188	60.05254	67.516	2.88	72.25	357.30	361.29	28.46
8000	0.00189	7.84945	63.17164	71.023	3.03	76.01	375.86	380.06	29.94
8200	0.00199	8.24683	66.36970	74.619	3.18	79.85	394.88	399.30	31.46
8400	0.00209	8.65402	69.64673	78.303	3.34	83.80	414.38	419.01	33.01
8600	0.00219	9.07102	73.00272	82.076	3.50	87.83	434.35	439.20	34.60
8800	0.00229	9.49783	76.43768	85.938	3.66	91.97	454.78	459.87	36.23
9000	0.00240	9.93446	79.95160	89.888	3.83	96.20	475.69	481.01	37.90
9200	0.00250	10.38090	83.54449	93.928	4.00	100.52	497.07	502.63	39.60
9400	0.00261	10.83715	87.21634	98.056	4.18	104.94	518.92	524.72	41.34

Kinetic Energy Storage: E = K*I*ω^2

where (ω^2) = (w*2*Pi/60)^2)

Shaft Inertia (thick cylinder): I_{shaft} = 0.5*m*(R1^2 +R2^2)

Hub-disk Inertia (thick cylinder): I_{hub} = 0.5*m*(R2^2 +R3^2)

Solid Cylinder Radial Stress: $\sigma_{r\_max} = \sigma_{t\_max} = \rho\omega^2(3-2\upsilon)/8(1-\upsilon))R_4^2$

Hollow Cylinder Radial Stress: $\sigma_{r\_max} = \rho\omega^2(3-2\upsilon)/8(1-\upsilon)((R_4^2 - R_3^2)$...

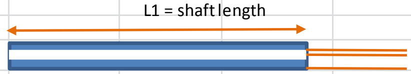
Hollow Cylinder Hoop Stress: $\sigma_{t\_max} = \rho\omega^2/4(1-\upsilon)[(1-2\upsilon)R_3^2 + (3-2\upsilon)R_4^2]$

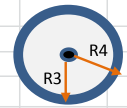
Target Design is >=15% over KWh requirement with 40% safety factor for metal rotors and 25% safety actord for composite rotors

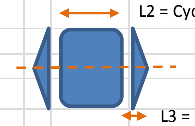
Hub disk composits oriented for radial strength Cylinder oriented for hoop strength

Reinforced 3-D disk rotor design with Aluminum 2014-T6 alloy

Pi =	3.141592654
~1.4 safety factor	
~1.25 safety factor	







Shaft Specifications

0.33	Poisson's Ratio
2800	Shaft material density
414	Shaft material (MPa)
Al	Shaft Material Description

Overwrap Specifications

0.33	Poisson's Ratio
2800	Overwrap material density kg/m^3
414	Overwrap MPa tensile strength
Al	Overwrap Material Description

Rim Specifications

0.33	Poisson's Ratio
2800	Rim material density (kg/m^3)
414	Rim MPa tensile strength (MPa)
Al	Hub & Disk Material Description

Design Specifications

0.8	Rim K factor
0.9	Overwrap disk K factor
0.5	Shaft K factor
0.98	Storage effeciency

Flywheel Specs

3.9726	Shaft length, l1 (m)	0.00	Overwrap Disk mass, each side (kg)	2940.00	Rim cylinder mass (kg)	50	Energy storage target kWh
0.03	Shaft radius, R2 (m)	0.0000	Overwrap volume (m^3)	0.7500	Cylinder inner diameter (% of radius)	0.4500	Rotor Rim Outer Radius, R5 (m)
0	Shaft inner radius, R1 (m)	0.00	Overwrap height, L3 (m)	1.0500	Rim structure volume (m^3)	3.7726	Rotor Rim Cylinder Height, L2 (m)
31.45	Shaft mass (kg)	0.000	Overwrap Inertia, each side (kg-m^2)	465.117	Rim Cylinder Inertia (kg-m^2)	2971.45	Total Rotor + shaft Mass (kg)
0.014	Shaft Inertia (kg-m^2)	0	Overwrap top thickness (m)	0.3375	Cylinder inner diameter, R3 (m)	16.83	Watts-hr/kg estimate
Rev step:	200	0.00	Effective Density (kg/m^3)	0.4500	Cylinder outer diameter, R4 (m)	0.020833	kWh/liter estimate

Rotor rev/min	Stored Energy (shaft) kWh	Stored Energy (Overwrap) (kWh)	Stored Energy (Cylinder) (kWh)	Total Energy Stored (kWh)	Shaft Hoop or radial Stress (Mpa)	Cylinder Radial Stress (MPa)	Cylinder Hoop Stress (MPa)	Overwrap Radial Stress (Mpa)	Overwrap Hoop Stress (Mpa)
5000	0.00053	0.00000	27.76983	27.770	0.00	29.69	146.82	0.00	146.82
5200	0.00057	0.00000	30.03585	30.036	0.00	32.11	158.80	0.00	158.80
5400	0.00062	0.00000	32.39073	32.391	0.00	34.63	171.25	0.00	171.25
5600	0.00066	0.00000	34.83447	34.835	0.00	37.24	184.17	0.00	184.17
5800	0.00071	0.00000	37.36708	37.368	0.00	39.95	197.56	0.00	197.56
6000	0.00076	0.00000	39.98855	39.989	0.00	42.75	211.42	0.00	211.42
6200	0.00081	0.00000	42.69889	42.700	0.00	45.65	225.75	0.00	225.75
6400	0.00087	0.00000	45.49809	45.499	0.00	48.64	240.55	0.00	240.55
6600	0.00092	0.00000	48.38615	48.387	0.00	51.73	255.82	0.00	255.82
6800	0.00098	0.00000	51.36307	51.364	0.00	54.91	271.56	0.00	271.56
7000	0.00104	0.00000	54.42886	54.430	0.00	58.19	287.76	0.00	287.76
7200	**0.00110**	**0.00000**	**57.58352**	**57.585**	**0.00**	**61.57**	**304.44**	**0.00**	**304.44**
7400	0.00116	0.00000	60.82703	60.828	0.00	65.03	321.59	0.00	321.59
7600	0.00122	0.00000	64.15941	64.161	0.00	68.60	339.21	0.00	339.21
7800	0.00129	0.00000	67.58065	67.582	0.00	72.25	357.30	0.00	357.30
8000	0.00135	0.00000	71.09076	71.092	0.00	76.01	375.86	0.00	375.86
8200	0.00142	0.00000	74.68973	74.691	0.00	79.85	394.88	0.00	394.88
8400	0.00149	0.00000	78.37756	78.379	0.00	83.80	414.38	0.00	414.38
8600	0.00156	0.00000	82.15426	82.156	0.00	87.83	434.35	0.00	434.35
8800	0.00164	0.00000	86.01982	86.021	0.00	91.97	454.78	0.00	454.78
9000	0.00171	0.00000	89.97424	89.976	0.00	96.20	475.69	0.00	475.69
9200	0.00179	0.00000	94.01753	94.019	0.00	100.52	497.07	0.00	497.07
9400	0.00187	0.00000	98.14968	98.152	0.00	104.94	518.92	0.00	518.92

Kinetic Energy Storage: $E = K*I*\omega^2$

where $(\omega^2) = (w*2*Pi/60)^2)$

Shaft Inertia (thick cylinder): $I_{shaft} = 0.5*m*(R1^2 + R2^2)$

Hub-disk Inertia (thick cylinder): $I_{hub} = 0.5*m*(R2^2 + R3^2)$

Conical disk interia: $I_{overwrap} = 3/10*m*R4^2$

Solid Cylinder Radial Stress: $\sigma_{r\_max} = \sigma_{t\_max} = \rho\omega^2(3-2\upsilon)/8(1-\upsilon))R_4^2$

Hollow Cylinder Radial Stress: $\sigma_{r\_max} = \rho\omega^2(3-2\upsilon)/8(1-\upsilon)((R_4^2 - R_3^2)$...

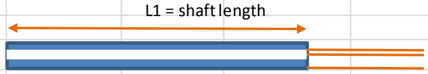
Hollow Cylinder Hoop Stress: $\sigma_{t\_max} = \rho\omega^2/4(1-\upsilon)[(1-2\upsilon)R_3^2 + (3-2\upsilon)R_4^2]$

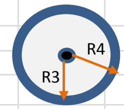
Target Design is >=15% over KWh requirement with 40% safety factor for metal rotors and 25% safety actord for composite rotors

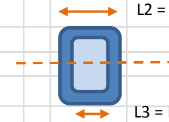
Assume K=0.8 for the advanced flywheel while using the Cylinder stress equations since complex toroidal stress analysis equations are unavailable.

Solid cylinder rotor design with Steel ASTM A514 Alloy

Pi =	3.141592654
~1.4 safety factor	
~1.25 safety factor	







Shaft Specifications

0.29	Poisson's Ratio
7800	Shaft material density
690	Shaft material (MPa)
Steel	Shaft Material Description

Hub Specifications

0.29	Poisson's Ratio
7800	Hub & disk material density kg/m^3
690	Hub & disk MPa tensile strength
Steel	Hub & Disk Material Description

Rim Specifications

0.29	Poisson's Ratio
7800	Rim material density (kg/m^3)
690	Rim MPa tensile strength (MPa)
Steel	Hub & Disk Material Description

Design Specifications

0.4	Rim K factor
0	Hub disk K factor
0.5	Shaft K factor
0.98	Storage effeciency

Flywheel Specs

3.0502	Shaft length, l1 (m)	0.0000	Hub-Disk Length, L3 (m)	14080.00	Rim cylinder mass (kg)	50	Energy storage target kWh
0.03	Shaft radius, R2 (m)	0.0000	Hub-Disk volume (m^3)	0.0668	Cylinder inner diameter (% of radius)	0.4500	Rotor Rim Outer Radius, R4 (m)
0	Shaft inner radius, R1 (m)	0.00	Hub-Disk mass (kg)	1.8051	Rim structure volume (m^3)	2.8502	Rotor Rim Cylinder Height, L2 (m)
67.27	Shaft mass (kg)	7800.00	Hub-disk effective Density (kg/m^3)	1431.961369	Rim Cylinder Inertia (kg-m^2)	14147.27	Total Rotor + shaft Mass (kg)
0.030	Shaft Inertia (kg-m^2)	0.000	Hub-Disk Inertia (kg-m^2)	0.03006	Cylinder inner diameter, R3 (m)	3.53	Watts-hr/kg estimate
Rev step	200					0.027575	kWh/liter estimate

Rotor rev/min	Stored Energy (shaft) (kWh)	Stored Energy (Hub) (kWh)	Stored Energy (Cylinder) (kWh)	Total Energy Stored (kWh)	Shaft Hoop or radial Stress est. (Mpa)	Cylinder Radial Stress (MPa)	Cylinder Hoop Stress (MPa)	Hub-Disk Radial Stress (Mpa)	Hub-Disk Hoop Stress (Mpa)
4000	0.00072	0.00000	27.35849	27.359	0.52	117.55	236.34	0.00	1.24
4200	0.00080	0.00000	30.16273	30.164	0.58	129.60	260.56	0.00	1.36
4400	0.00087	0.00000	33.10377	33.105	0.63	142.24	285.97	0.00	1.50
4600	0.00096	0.00000	36.18160	36.183	0.69	155.46	312.55	0.00	1.63
4800	0.00104	0.00000	39.39622	39.397	0.76	169.27	340.32	0.00	1.78
5000	0.00113	0.00000	42.74764	42.749	0.82	183.67	369.28	0.00	1.93
5200	0.00122	0.00000	46.23584	46.237	0.89	198.66	399.41	0.00	2.09
5400	0.00132	0.00000	49.86084	49.862	0.96	214.23	430.72	0.00	2.25
5600	0.00142	0.00000	53.62264	53.624	1.03	230.40	463.22	0.00	2.42
5800	**0.00152**	**0.00000**	**57.52122**	**57.523**	**1.10**	**247.15**	**496.90**	**0.00**	**2.60**
6000	0.00163	0.00000	61.55660	61.558	1.18	264.49	531.76	0.00	2.78
6200	0.00174	0.00000	65.72877	65.731	1.26	282.41	567.80	0.01	2.97
6400	0.00185	0.00000	70.03773	70.040	1.34	300.93	605.02	0.01	3.16
6600	0.00197	0.00000	74.48348	74.485	1.43	320.03	643.43	0.01	3.36
6800	0.00209	0.00000	79.06603	79.068	1.52	339.72	683.01	0.01	3.57
7000	0.00221	0.00000	83.78537	83.788	1.61	360.00	723.78	0.01	3.79
7200	0.00234	0.00000	88.64150	88.644	1.70	380.86	765.73	0.01	4.00
7400	0.00247	0.00000	93.63442	93.637	1.80	402.31	808.86	0.01	4.23
7600	0.00261	0.00000	98.76414	98.767	1.89	424.35	853.17	0.01	4.46
7800	0.00275	0.00000	104.03065	104.033	2.00	446.98	898.67	0.01	4.70
8000	0.00289	0.00000	109.43395	109.437	2.10	470.20	945.34	0.01	4.94
8200	0.00304	0.00000	114.97404	114.977	2.21	494.00	993.20	0.01	5.19
8400	0.00319	0.00000	120.65093	120.654	2.31	518.39	1042.24	0.01	5.45

Kinetic Energy Storage: E = K*I*ω^2

where (ω^2) = (w*2*Pi/60)^2)

Shaft Inertia (thick cylinder): $I_{shaft} = 0.5*m*(R1^2 + R2^2)$

Hub-disk Inertia (thick cylinder): $I_{hub} = 0.5*m*(R2^2 + R3^2)$

Solid Cylinder Radial Stress: $\sigma_{r\_max} = \sigma_{t\_max} = \rho\omega^2(3-2\upsilon)/8(1-\upsilon))R_4^2$

Hollow Cylinder Radial Stress: $\sigma_{r\_max} = (\rho\omega^2(3-2\upsilon)/8(1-\upsilon))*(R_4^2 - R_3^2)$

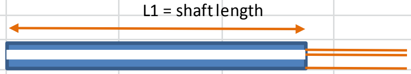
Hollow Cylinder Hoop Stress: $\sigma_{t\_max} = \rho\omega^2/4(1-\upsilon)[(1-2\upsilon)R_3^2 + (3-2\upsilon)R_4^2]$

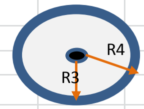
Target Design is >=15% over KWh requirement with 40% safety factor for metal rotors and 25% safety actord for composite rotors

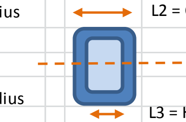
Assume K=0.4 for the solid cylinder flywheel due to radial composit wrap not optimal for radial stress.

Hollow cylinder + hub rotor design with Steel ASTM A514 alloy

Pi =	3.141592654
~1.4 safety factor	
~1.25 safety factor	







Shaft Specifications		Hub Specifications		Rim Specifications		Design Specifications	
0.29	Poisson's Ratio	0.29	Poisson's Ratio	0.29	Poisson's Ratio	0.5	Rim K factor
7800	Shaft material density	7800	Hub & disk material density kg/m^3	7800	Rim material density (kg/m^3)	0.5	Hub disk K factor
690	Shaft material (MPa)	690	Hub & disk MPa tensile strength	690	Rim MPa tensile strength (MPa)	0.5	Shaft K factor
Steel	Shaft Material Description	Steel	Hub & Disk Material Description	Steel	Hub & Disk Material Description	0.98	Storage effeciency

Flywheel Specs							
3.3876	Shaft length, l1 (m)	0.8500	Hub-Disk Length, L3 (m)	6920.00	Rim cylinder mass (kg)	50	Energy storage target kWh
0.03	Shaft radius, R2 (m)	0.3018	Hub-Disk volume (m^3)	0.7500	Cylinder inner diameter (% of radius)	0.4500	Rotor Rim Outer Radius, R4 (m)
0	Shaft inner radius, R1 (m)	2353.78	Hub-Disk mass (kg)	0.8872	Rim structure volume (m^3)	3.1876	Rotor Rim Cylinder length L2 (m)
74.71	Shaft mass (kg)	30731.63	Hub-disk effective Density (kg/m^3)	1094.765625	Rim Cylinder Inertia (kg-m^2)	9348.49	Total Rotor + shaft Mass (kg)
0.034	Shaft Inertia (kg-m^2)	135.114	Hub-Disk Inertia (kg-m^2)	0.3375	Cylinder inner diameter, R3 (m)	5.35	Watts-hr/kg estimate
Rev step	200					0.024657	kWh/liter estimate

Rotor rev/min	Stored Energy (shaft) (kWh)	Stored Energy (Hub) (kWh)	Stored Energy (Cylinder) (kWh)	Total Energy Stored (kWh)	Shaft Hoop or radial Stress (Mpa)	Cylinder Radial Stress (MPa)	Cylinder Hoop Stress (MPa)	Hub-Disk Radial Stress (Mpa)	Hub-Disk Hoop Stress (Mpa)
4000	0.00080	3.22680	26.14520	29.373	2.07	51.66	259.21	259.62	24.10
4200	0.00089	3.55755	28.82508	32.384	2.28	56.95	285.78	286.23	26.57
4400	0.00097	3.90443	31.63569	35.541	2.50	62.51	313.64	314.14	29.17
4600	0.00106	4.26744	34.57703	38.846	2.73	68.32	342.80	343.34	31.88
4800	0.00116	4.64659	37.64909	42.297	2.98	74.39	373.26	373.85	34.71
5000	0.00125	5.04188	40.85187	45.895	3.23	80.72	405.01	405.65	37.66
5200	0.00136	5.45329	44.18539	49.640	3.49	87.30	438.06	438.75	40.74
5400	0.00146	5.88085	47.64963	53.532	3.77	94.15	472.41	473.15	43.93
5600	**0.00157**	**6.32453**	**51.24459**	**57.571**	**4.05**	**101.25**	**508.05**	**508.85**	**47.24**
5800	0.00169	6.78435	54.97028	61.756	4.35	108.61	544.98	545.84	50.68
6000	0.00181	7.26030	58.82670	66.089	4.65	116.23	583.22	584.14	54.23
6200	0.00193	7.75239	62.81384	70.568	4.97	124.11	622.75	623.73	57.91
6400	0.00206	8.26061	66.93171	75.194	5.29	132.25	663.57	664.62	61.71
6600	0.00219	8.78497	71.18030	79.967	5.63	140.64	705.69	706.81	65.62
6800	0.00232	9.32546	75.55962	84.887	5.98	149.29	749.11	750.29	69.66
7000	0.00246	9.88208	80.06967	89.954	6.33	158.20	793.82	795.08	73.82
7200	0.00260	10.45484	84.71044	95.168	6.70	167.37	839.83	841.16	78.10
7400	0.00275	11.04373	89.48194	100.528	7.08	176.80	887.14	888.54	82.50
7600	0.00290	11.64875	94.38417	106.036	7.46	186.49	935.74	937.22	87.01
7800	0.00305	12.26991	99.41712	111.690	7.86	196.43	985.64	987.19	91.65
8000	0.00321	12.90720	104.58080	117.491	8.27	206.63	1036.83	1038.47	96.42
8200	0.00337	13.56063	109.87520	123.439	8.69	217.09	1089.32	1091.04	101.30
8400	0.00354	14.23019	115.30033	129.534	9.12	227.81	1143.10	1144.91	106.30

Kinetic Energy Storage: $E = K*I*\omega^2$

where $(\omega^2) = (w*2*Pi/60)^2$

Shaft Inertia (thick cylinder): $I_{shaft} = 0.5*m*(R1^2 + R2^2)$

Hub-disk Inertia (thick cylinder): $I_{hub} = 0.5*m*(R2^2 + R3^2)$

Solid Cylinder Radial Stress: $\sigma_{r\_max} = \sigma_{t\_max} = \rho\omega^2(3-2\upsilon)/8(1-\upsilon))R_4^2$

Hollow Cylinder Radial Stress: $\sigma_{r\_max} = \rho\omega^2(3-2\upsilon)/8(1-\upsilon)((R_4^2 - R_3^2)$...

Hollow Cylinder Hoop Stress: $\sigma_{t\_max} = \rho\omega^2/4(1-\upsilon)[(1-2\upsilon)R_3^2 + (3-2\upsilon)R_4^2]$

Target Design is >=15% over KWh requirement
with 40% safety factor for metal rotors
and 25% safety actord for composite rotors

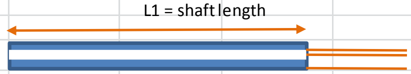
Hub disk composits oriented for radial strength
Cylinder oriented for hoop strength

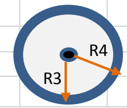
Reinforced 3-D disk rotor design with Steel ASTM A514 Alloy

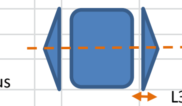
Pi =	3.141592654

~1.4 safety factor

~1.25 safety factor







Shaft Specifications

0.29	Poisson's Ratio
7800	Shaft material density
690	Shaft material (MPa)
Steel	Shaft Material Description

Overwrap Specifications

0.29	Poisson's Ratio
7800	Overwrap material density kg/m^3
690	Overwrap MPa tensile strength
Steel	Overwrap Material Description

Rim Specifications

0.29	Poisson's Ratio
7800	Rim material density (kg/m^3)
690	Rim MPa tensile strength (MPa)
Steel	Hub & Disk Material Description

Design Specifications

0.8	Rim K factor
0.9	Overwrap disk K factor
0.5	Shaft K factor
0.98	Storage effeciency

Flywheel Specs

2.4387	Shaft length, l1 (m)
0.03	Shaft radius, R2 (m)
0	Shaft inner radius, R1 (m)
53.78	Shaft mass (kg)
0.024	Shaft Inertia (kg-m^2)
Rev step:	200

0.00	Overwrap Disk mass, each side (kg)
0.0000	Overwrap volume (m^3)
0.00	Overwrap height, L3 (m)
0.000	Overwrap Inertia, each side (kg-m^2)
0	Overwrap top thickness (m)
0.00	Effective Density (kg/m^3)

4860.00	Rim cylinder mass (kg)
0.7500	Cylinder inner diameter (% of radius)
0.6231	Rim structure volume (m^3)
768.867	Rim Cylinder Inertia (kg-m^2)
0.3375	Cylinder inner diameter, R3 (m)
0.4500	Cylinder outer diameter, R4 (m)

50	Energy storage target kWh
0.4500	Rotor Rim Outer Radius, R5 (m)
2.2387	Rotor Rim Cylinder Height, L2 (m)
4913.78	Total Rotor + shaft Mass (kg)
10.18	Watts-hr/kg estimate
0.035108	kWh/liter estimate

Rotor rev/min	Stored Energy (shaft) kWh	Stored Energy (Overwrap) (kWh)	Stored Energy (Cylinder) (kWh)	Total Energy Stored (kWh)	Shaft Hoop or radial Stress (Mpa)	Cylinder Radial Stress (MPa)	Cylinder Hoop Stress (MPa)	Overwrap Radial Stress (Mpa)	Overwrap Hoop Stress (Mpa)
4000	0.00058	0.00000	29.37934	29.380	0.00	51.66	259.21	0.00	259.21
4200	0.00064	0.00000	32.39073	32.391	0.00	56.95	285.78	0.00	285.78
4400	0.00070	0.00000	35.54901	35.550	0.00	62.51	313.64	0.00	313.64
4600	0.00076	0.00000	38.85418	38.855	0.00	68.32	342.80	0.00	342.80
4800	0.00083	0.00000	42.30626	42.307	0.00	74.39	373.26	0.00	373.26
5000	0.00090	0.00000	45.90523	45.906	0.00	80.72	405.01	0.00	405.01
5200	0.00098	0.00000	49.65109	49.652	0.00	87.30	438.06	0.00	438.06
5400	0.00105	0.00000	53.54386	53.545	0.00	94.15	472.41	0.00	472.41
5600	**0.00113**	**0.00000**	**57.58352**	**57.585**	**0.00**	**101.25**	**508.05**	**0.00**	**508.05**
5800	0.00122	0.00000	61.77007	61.771	0.00	108.61	544.98	0.00	544.98
6000	0.00130	0.00000	66.10353	66.105	0.00	116.23	583.22	0.00	583.22
6200	0.00139	0.00000	70.58388	70.585	0.00	124.11	622.75	0.00	622.75
6400	0.00148	0.00000	75.21112	75.213	0.00	132.25	663.57	0.00	663.57
6600	0.00157	0.00000	79.98527	79.987	0.00	140.64	705.69	0.00	705.69
6800	0.00167	0.00000	84.90631	84.908	0.00	149.29	749.11	0.00	749.11
7000	0.00177	0.00000	89.97424	89.976	0.00	158.20	793.82	0.00	793.82
7200	0.00187	0.00000	95.18908	95.191	0.00	167.37	839.83	0.00	839.83
7400	0.00198	0.00000	100.55081	100.553	0.00	176.80	887.14	0.00	887.14
7600	0.00209	0.00000	106.05944	106.062	0.00	186.49	935.74	0.00	935.74
7800	0.00220	0.00000	111.71496	111.717	0.00	196.43	985.64	0.00	985.64
8000	0.00231	0.00000	117.51738	117.520	0.00	206.63	1036.83	0.00	1036.83
8200	0.00243	0.00000	123.46670	123.469	0.00	217.09	1089.32	0.00	1089.32
8400	0.00255	0.00000	129.56291	129.565	0.00	227.81	1143.10	0.00	1143.10

Kinetic Energy Storage: E = K*I*ω^2

where (ω^2) = (w*2*Pi/60)^2)

Shaft Inertia (thick cylinder): I_{shaft} = 0.5*m*(R1^2 +R2^2)

Hub-disk Inertia (thick cylinder): I_{hub} = 0.5*m*(R2^2 +R3^2)

Conical disk interia: $I_{overwrap}$ = 3/10*m*R4^2

Solid Cylinder Radial Stress: $\sigma_{r\_max} = \sigma_{t\_max} = \rho\omega^2(3-2\upsilon)/8(1-\upsilon))R_4^2$

Hollow Cylinder Radial Stress: $\sigma_{r\_max} = \rho\omega^2(3-2\upsilon)/8(1-\upsilon)((R_4^2 - R_3^2)$...

Hollow Cylinder Hoop Stress: $\sigma_{t\_max} = \rho\omega^2/4(1-\upsilon)[(1-2\upsilon)R_3^2 + (3-2\upsilon)R_4^2]$

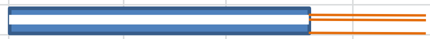
Target Design is >=15% over KWh requirement with 40% safety factor for metal rotors and 25% safety actord for composite rotors

Assume K=0.8 for the advanced flywheel while using the Cylinder stress equations since complex toroidal stress analysis equations are unavailable.

Solid cylinder rotor design with E-Glass composite

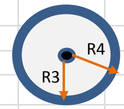
Pi =	3.141592654
~1.4 safety factor	
~1.25 safety factor	

L1 = shaft length



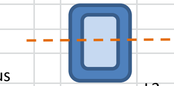
R1 = inner shaft radius
R2 = outer shaft radius

R3 = Cycinder Inner Radius



R4 = Cycinder Outer Radius

L2 = Cyclinder length



L3 = Hub length

Shaft Specifications		Hub Specifications		Rim Specifications		Design Specifications	
0.28	Poisson's Ratio	0.28	Poisson's Ratio	0.28	Poisson's Ratio	0.4	Rim K factor
2120	Shaft material density	2120	Hub & disk material density kg/m^3	2120	Rim material density (kg/m^3)	0	Hub disk K factor
1408	Shaft material (MPa)	1408	Hub & disk MPa tensile strength	1408	Rim MPa tensile strength (MPa)	0.5	Shaft K factor
E-Glass	Shaft Material Description	E-Glass	Hub & Disk Material Description	E-Glass	Hub & Disk Material Description	0.98	Storage effeciency

Flywheel Specs							
1.3857	Shaft length, l1 (m)	0.0000	Hub-Disk Length, L3 (m)	1592.00	Rim cylinder mass (kg)	50	Energy storage target kWh
0.03	Shaft radius, R2 (m)	0.0000	Hub-Disk volume (m^3)	0.0668	Cylinder inner diameter (% of radius)	0.4500	Rotor Rim Outer Radius, R4 (m)
0.02	Shaft inner radius, R1 (m)	0.00	Hub-Disk mass (kg)	0.7509	Rim structure volume (m^3)	1.1857	Rotor Rim Cylinder Height, L2 (m)
4.61	Shaft mass (kg)	2120.00	Hub-disk effective Density (kg/m^3)	161.9092685	Rim Cylinder Inertia (kg-m^2)	1596.61	Total Rotor + shaft Mass (kg)
0.003	Shaft Inertia (kg-m^2)	0.000	Hub-Disk Inertia (kg-m^2)	0.03006	Cylinder inner diameter, R3 (m)	31.32	Watts-hr/kg estimate
Rev step	250					0.066286	kWh/liter estimate

Rotor rev/min	Stored Energy (shaft) (kWh)	Stored Energy (Hub) (kWh)	Stored Energy (Cylinder) (kWh)	Total Energy Stored (kWh)	Shaft Hoop or radial Stress est. (Mpa)	Cylinder Radial Stress (MPa)	Cylinder Hoop Stress (MPa)	Hub-Disk Radial Stress (Mpa)	Hub-Disk Hoop Stress (Mpa)
14000	0.00088	0.00000	37.89384	37.895	1.74	389.13	782.39	0.01	4.11
14250	0.00091	0.00000	39.25927	39.260	1.80	403.16	810.58	0.01	4.26
14500	0.00094	0.00000	40.64887	40.650	1.86	417.43	839.27	0.01	4.41
14750	0.00097	0.00000	42.06264	42.064	1.93	431.94	868.46	0.01	4.57
15000	0.00101	0.00000	43.50058	43.502	1.99	446.71	898.15	0.01	4.72
15250	0.00104	0.00000	44.96268	44.964	2.06	461.72	928.33	0.01	4.88
15500	0.00108	0.00000	46.44895	46.450	2.13	476.99	959.02	0.01	5.04
15750	0.00111	0.00000	47.95939	47.960	2.20	492.50	990.21	0.01	5.21
16000	0.00115	0.00000	49.49399	49.495	2.27	508.26	1021.89	0.01	5.37
16250	0.00118	0.00000	51.05276	51.054	2.34	524.26	1054.08	0.01	5.54
16500	0.00122	0.00000	52.63570	52.637	2.41	540.52	1086.76	0.01	5.72
16750	0.00126	0.00000	54.24280	54.244	2.49	557.02	1119.94	0.01	5.89
17000	0.00129	0.00000	55.87408	55.875	2.56	573.77	1153.62	0.01	6.07
17250	0.00133	0.00000	57.52951	57.531	2.64	590.77	1187.80	0.01	6.25
17500	0.00137	0.00000	59.20912	59.210	2.71	608.02	1222.48	0.01	6.43
17750	0.00141	0.00000	60.91289	60.914	2.79	625.52	1257.65	0.01	6.61
18000	0.00145	0.00000	62.64083	62.642	2.87	643.26	1293.33	0.01	6.80
18250	0.00149	0.00000	64.39294	64.394	2.95	661.25	1329.51	0.01	6.99
18500	0.00153	0.00000	66.16921	66.171	3.03	679.50	1366.18	0.01	7.19
18750	0.00157	0.00000	67.96965	67.971	3.12	697.98	1403.35	0.01	7.38
19000	0.00162	0.00000	69.79426	69.796	3.20	716.72	1441.03	0.01	7.58
19250	0.00166	0.00000	71.64304	71.645	3.28	735.71	1479.20	0.01	7.78
19500	0.00170	0.00000	73.51598	73.518	3.37	754.94	1517.87	0.01	7.98

Kinetic Energy Storage: $E = K*I*\omega^2$
where $(\omega^2) = (w*2*Pi/60)^2)$

Shaft Inertia (thick cylinder): $I_{shaft} = 0.5*m*(R1^2 + R2^2)$

Hub-disk Inertia (thick cylinder): $I_{hub} = 0.5*m*(R2^2 + R3^2)$

Solid Cylinder Radial Stress: $\sigma_{r\_max} = \sigma_{t\_max} = \rho\omega^2(3-2\upsilon)/8(1-\upsilon))R_4^2$

Hollow Cylinder Radial Stress: $\sigma_{r\_max} = (\rho\omega^2(3-2\upsilon)/8(1-\upsilon))*(R_4^2 - R_3^2)$

Hollow Cylinder Hoop Stress: $\sigma_{t\_max} = \rho\omega^2/4(1-\upsilon)\,[\,(1-2\upsilon)R_3^2 + (3-2\upsilon)R_4^2]$

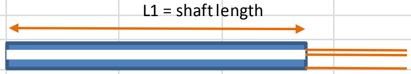
Target Design is >=15% over KWh requirement at break point of 40% and 25% safety factor

Assume K=0.4 for the solid cylinder flywheel due to radial composit wrap not optimal for radial stress.

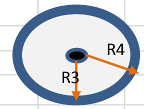
Hollow cylinder + hub rotor design with E-Glass composite

Pi =	3.141592654
~1.4 safety factor	
~1.25 safety factor	

L1 = shaft length

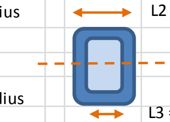


R1 = inner shaft radius
R2 = outer shaft radius



R3 = Cyclinder Inner Radius
R4 = Cyclinder Outer Radius

L2 = Cyclinder length



L3 = Hub length

Shaft Specifications

0.28	Poisson's Ratio
2120	Shaft material density
1408	Shaft material (MPa)
E-Glass	Shaft Material Description

Hub Specifications

0.28	Poisson's Ratio
2120	Hub & disk material density kg/m^3
1408	Hub & disk MPa tensile strength
E-Glass	Hub & Disk Material Description

Rim Specifications

0.28	Poisson's Ratio
2120	Rim material density (kg/m^3)
1408	Rim MPa tensile strength (MPa)
E-Glass	Hub & Disk Material Description

Design Specifications

0.5	Rim K factor
0.5	Hub disk K factor
0.5	Shaft K factor
0.98	Storage effeciency

Flywheel Specs

1.5507	Shaft length, l1 (m)
0.03	Shaft radius, R2 (m)
0.02	Shaft inner radius, R1 (m)
5.16	Shaft mass (kg)
0.003	Shaft Inertia (kg-m^2)
Rev step	500

0.3600	Hub-Disk Length, L3 (m)
0.1278	Hub-Disk volume (m^3)
270.95	Hub-Disk mass (kg)
8355.96	Hub-disk effective Density (kg/m^3)
15.553	Hub-Disk Inertia (kg-m^2)

797.00	Rim cylinder mass (kg)
0.7500	Cylinder inner diameter (% of radius)
0.3759	Rim structure volume (m^3)
126.0878906	Rim Cylinder Inertia (kg-m^2)
0.3375	Cylinder inner diameter, R3 (m)

50	Energy storage target kWh
0.4500	Rotor Rim Outer Radius, R4 (m)
1.3507	Rotor Rim Cylinder length L2 (m)
1073.12	Total Rotor + shaft Mass (kg)
46.59	Watts-hr/kg estimate
0.058187	kWh/liter estimate

Rotor rev/min	Stored Energy (shaft) (kWh)	Stored Energy (Hub) (kWh)	Stored Energy (Cylinder) (kWh)	Total Energy Stored (kWh)	Shaft Hoop or radial Stress (Mpa)	Cylinder Radial Stress (MPa)	Cylinder Hoop Stress (MPa)	Hub-Disk Radial Stress (Mpa)	Hub-Disk Hoop Stress (Mpa)
12000	0.00072	3.34302	27.10109	30.445	5.03	125.64	632.61	631.66	60.81
12500	0.00078	3.62741	29.40656	33.035	5.46	136.33	686.43	685.40	65.98
13000	0.00085	3.92341	31.80614	35.730	5.90	147.45	742.44	741.33	71.37
13500	0.00091	4.23102	34.29981	38.532	6.37	159.01	800.65	799.45	76.96
14000	0.00098	4.55023	36.88759	41.439	6.85	171.01	861.05	859.76	82.77
14500	0.00105	4.88105	39.56947	44.452	7.35	183.44	923.66	922.27	88.79
15000	0.00113	5.22348	42.34545	47.570	7.86	196.31	988.45	986.97	95.02
15500	0.00120	5.57751	45.21553	50.794	8.39	209.62	1055.45	1053.87	101.46
16000	0.00128	5.94315	48.17971	54.124	8.94	223.36	1124.64	1122.96	108.11
16500	**0.00136**	**6.32041**	**51.23799**	**57.560**	**9.51**	**237.54**	**1196.03**	**1194.24**	**114.97**
17000	0.00145	6.70926	54.39037	61.101	10.10	252.15	1269.61	1267.71	122.05
17500	0.00153	7.10973	57.63686	64.748	10.70	267.20	1345.40	1343.38	129.33
18000	0.00162	7.52180	60.97744	68.501	11.32	282.69	1423.37	1421.24	136.83
18500	0.00171	7.94549	64.41213	72.359	11.96	298.61	1503.55	1501.30	144.53
19000	0.00181	8.38078	67.94092	76.324	12.61	314.97	1585.92	1583.55	152.45
19500	0.00191	8.82767	71.56380	80.393	13.28	331.77	1670.49	1667.99	160.58
20000	0.00200	9.28618	75.28079	84.569	13.97	349.00	1757.25	1754.62	168.92
20500	0.00211	9.75629	79.09188	88.850	14.68	366.67	1846.21	1843.45	177.47
21000	0.00221	10.23801	82.99707	93.237	15.41	384.77	1937.37	1934.47	186.24
21500	0.00232	10.73134	86.99637	97.730	16.15	403.31	2030.72	2027.68	195.21
22000	0.00242	11.23628	91.08976	102.328	16.91	422.29	2126.28	2123.09	204.39
22500	0.00254	11.75282	95.27725	107.033	17.69	441.70	2224.02	2220.69	213.79
23000	0.00265	12.28097	99.55885	111.842	18.48	461.55	2323.97	2320.49	223.40

Kinetic Energy Storage: E = K*I*ω^2

where (ω^2) = (w*2*Pi/60)^2)

Shaft Inertia (thick cylinder): I_{shaft} = 0.5*m*(R1^2 +R2^2)

Hub-disk Inertia (thick cylinder): I_{hub} = 0.5*m*(R2^2 +R3^2)

Solid Cylinder Radial Stress: $\sigma_{r\_max} = \sigma_{t\_max} = \rho\omega^2(3- 2\upsilon) /8(1-\upsilon))R_4^2$

Hollow Cylinder Radial Stress: $\sigma_{r\_max} = \rho\omega^2(3- 2\upsilon) /8(1-\upsilon) ((R_4^2 - R_3^2)$...

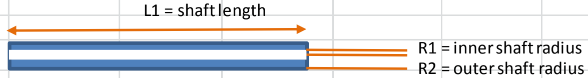
Hollow Cylinder Hoop Stress: $\sigma_{t\_max} = \rho\omega^2 /4(1-\upsilon) [(1 - 2\upsilon)R_3^2 + (3- 2\upsilon)R_4^2]$

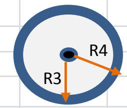
Target Design is >=15% over KWh requirement at break point of 40% and 25% safety factor

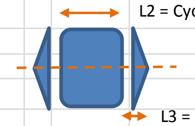
Hub disk composits oriented for radial strength
Cylinder oriented for hoop strength

Reinforced 3-D disk rotor design with E-Glass composite

Pi =	3.141592654
~1.4 safety factor	
~1.25 safety factor	







Shaft Specifications

0.28	Poisson's Ratio
2120	Shaft material density
1408	Shaft material (MPa)
E-Glass	Shaft Material Description

Overwrap Specifications

0.28	Poisson's Ratio
2120	Overwrap material density kg/m^3
1408	Overwrap MPa tensile strength
E-Glass	Overwrap Material Description

Rim Specifications

0.28	Poisson's Ratio
2120	Rim material density (kg/m^3)
1408	Rim MPa tensile strength (MPa)
E-Glass	Hub & Disk Material Description

Design Specifications

0.8	Rim K factor
0.9	Overwrap disk K factor
0.5	Shaft K factor
0.98	Storage effeciency

Flywheel Specs

1.3216	Shaft length, l1 (m)	92.00	Overwrap Disk mass, each side (kg)	480.00	Rim cylinder mass (kg)	50	Energy storage target kWh
0.03	Shaft radius, R2 (m)	0.0653	Overwrap volume (m^3)	0.7500	Cylinder inner diameter (% of radius)	0.4500	Rotor Rim Outer Radius, R5 (m)
0.02	Shaft inner radius, R1 (m)	0.15	Overwrap height, L3 (m)	0.2264	Rim structure volume (m^3)	0.8135	Rotor Rim Cylinder Height, L2 (m)
4.40	Shaft mass (kg)	5.589	Overwrap Inertia, each side (kg-m^2)	75.938	Rim Cylinder Inertia (kg-m^2)	668.40	Total Rotor + shaft Mass (kg)
0.003	Shaft Inertia (kg-m^2)	0.030812826	Overwrap top thickness (m)	0.3375	Cylinder inner diameter, R3 (m)	74.81	Watts-hr/kg estimate
Rev step:	250	4377.04	Effective Density (kg/m^3)	0.4192	Cylinder outer diameter, R4 (m)	0.077136	kWh/liter estimate

Rotor rev/min	Stored Energy (shaft) kWh	Stored Energy (Overwrap) (kWh)	Stored Energy (Cylinder) (kWh)	Total Energy Stored (kWh)	Shaft Hoop or radial Stress (Mpa)	Cylinder Radial Stress (MPa)	Cylinder Hoop Stress (MPa)	Overwrap Radial Stress (Mpa)	Overwrap Hoop Stress (Mpa)
13000	0.00072	5.07545	30.64882	35.725	3.09	102.88	653.29	692.76	742.44
13250	0.00075	5.27253	31.83896	37.112	3.21	106.87	678.66	719.66	771.27
13500	0.00078	5.47337	33.05176	38.526	3.34	110.94	704.51	747.07	800.65
13750	0.00081	5.67797	34.28724	39.966	3.46	115.09	730.84	775.00	830.58
14000	0.00084	5.88631	35.54538	41.433	3.59	119.31	757.66	803.44	861.05
14250	0.00087	6.09842	36.82619	42.925	3.72	123.61	784.96	832.39	892.08
14500	0.00090	6.31427	38.12967	44.445	3.85	127.99	812.75	861.85	923.66
14750	0.00093	6.53388	39.45583	45.991	3.98	132.44	841.01	891.83	955.78
15000	0.00096	6.75725	40.80465	47.563	4.12	136.97	869.76	922.31	988.45
15250	0.00099	6.98437	42.17614	49.161	4.26	141.57	899.00	953.31	1021.68
15500	0.00103	7.21524	43.57029	50.787	4.40	146.25	928.71	984.83	1055.45
15750	0.00106	7.44987	44.98712	52.438	4.54	151.01	958.91	1016.85	1089.77
16000	0.00109	7.68825	46.42662	54.116	4.68	155.84	989.60	1049.39	1124.64
16250	0.00113	7.93038	47.88879	55.820	4.83	160.74	1020.76	1082.44	1160.06
16500	**0.00116**	**8.17627**	**49.37362**	**57.551**	**4.98**	**165.73**	**1052.41**	**1116.00**	**1196.03**
16750	0.00120	8.42591	50.88113	59.308	5.13	170.79	1084.55	1150.07	1232.55
17000	0.00123	8.67931	52.41130	61.092	5.29	175.93	1117.16	1184.66	1269.61
17250	0.00127	8.93646	53.96414	62.902	5.45	181.14	1150.26	1219.76	1307.23
17500	0.00131	9.19737	55.53966	64.738	5.60	186.43	1183.84	1255.37	1345.40
17750	0.00135	9.46203	57.13784	66.601	5.77	191.79	1217.91	1291.49	1384.11
18000	0.00138	9.73044	58.75869	68.491	5.93	197.23	1252.46	1328.13	1423.37
18250	0.00142	10.00261	60.40221	70.406	6.09	202.75	1287.49	1365.28	1463.19
18500	0.00146	10.27853	62.06840	72.348	6.26	208.34	1323.01	1402.94	1503.55

Kinetic Energy Storage: E = K*I*ω^2

where (ω^2) = (w*2*Pi/60)^2)

Shaft Inertia (thick cylinder): I_{shaft} = 0.5*m*(R1^2 +R2^2)

Hub-disk Inertia (thick cylinder): I_{hub} = 0.5*m*(R2^2 +R3^2)

Conical disk interia: $I_{overwrap}$ = 3/10*m*R4^2

Solid Cylinder Radial Stress: $\sigma_{r\_max} = \sigma_{t\_max} = \rho\omega^2(3-2\upsilon)/8(1-\upsilon))R_4^2$

Hollow Cylinder Radial Stress: $\sigma_{r\_max} = \rho\omega^2(3-2\upsilon)/8(1-\upsilon)((R_4^2 - R_3^2)$...

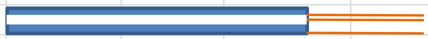
Hollow Cylinder Hoop Stress: $\sigma_{t\_max} = \rho\omega^2/4(1-\upsilon)[(1-2\upsilon)R_3^2 + (3-2\upsilon)R_4^2]$

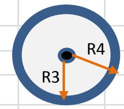
Target Design is >=15% over KWh requirement at break point of 40% and 25% safety factor

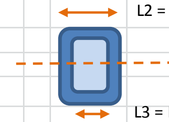
Assume K=0.8 for the advanced flywheel while using the Cylinder stress equations since complex toroidal stress analysis equations are unavailable. Overwrap modeled as a conical disk with an added thickness to the overwrap cylinder to take axial loads along composite fiber strength (K=0.9)

Solid cylinder rotor design with S-Glass composite

Pi =	3.141592654
~1.4 safety factor	
~1.25 safety factor	







Shaft Specifications		Hub Specifications		Rim Specifications		Design Specifications	
0.25	Poisson's Ratio	0.25	Poisson's Ratio	0.25	Poisson's Ratio	0.4	Rim K factor
1950	Shaft material density	1950	Hub & disk material density kg/m^3	1950	Rim material density (kg/m^3)	0	Hub disk K factor
2358	Shaft material (MPa)	2358	Hub & disk MPa tensile strength	2358	Rim MPa tensile strength (MPa)	0.5	Shaft K factor
S-Glass	Shaft Material Description	S-Glass	Hub & Disk Material Description	S-Glass	Hub & Disk Material Description	0.98	Storage effeciency

Flywheel Specs							
0.8964	Shaft length, l1 (m)	0.0000	Hub-Disk Length, L3 (m)	860.00	Rim cylinder mass (kg)	50	Energy storage target kWh
0.03	Shaft radius, R2 (m)	0.0000	Hub-Disk volume (m^3)	0.0668	Cylinder inner diameter (% of radius)	0.4500	Rotor Rim Outer Radius, R4 (m)
0.02	Shaft inner radius, R1 (m)	0.00	Hub-Disk mass (kg)	0.4410	Rim structure volume (m^3)	0.6964	Rotor Rim Cylinder Height, L2 (m)
2.75	Shaft mass (kg)	1950.00	Hub-disk effective Density (kg/m^3)	87.46354955	Rim Cylinder Inertia (kg-m^2)	862.75	Total Rotor + shaft Mass (kg)
0.002	Shaft Inertia (kg-m^2)	0.000	Hub-Disk Inertia (kg-m^2)	0.03006	Cylinder inner diameter, R3 (m)	57.95	Watts-hr/kg estimate
Rev step	250					0.112866	kWh/liter estimate

Rotor rev/min	Stored Energy (shaft) (kWh)	Stored Energy (Hub) (kWh)	Stored Energy (Cylinder) (kWh)	Total Energy Stored (kWh)	Shaft Hoop or radial Stress est. (Mpa)	Cylinder Radial Stress (MPa)	Cylinder Hoop Stress (MPa)	Hub-Disk Radial Stress (Mpa)	Hub-Disk Hoop Stress (Mpa)
20000	0.00107	0.00000	41.77610	41.777	3.21	718.49	1444.72	0.01	7.72
20250	0.00109	0.00000	42.82703	42.828	3.29	736.57	1481.06	0.01	7.92
20500	0.00112	0.00000	43.89101	43.892	3.37	754.87	1517.86	0.01	8.12
20750	0.00115	0.00000	44.96805	44.969	3.45	773.39	1555.10	0.01	8.31
21000	0.00117	0.00000	46.05815	46.059	3.54	792.14	1592.80	0.01	8.52
21250	0.00120	0.00000	47.16130	47.163	3.62	811.11	1630.95	0.01	8.72
21500	0.00123	0.00000	48.27751	48.279	3.71	830.31	1669.55	0.01	8.93
21750	0.00126	0.00000	49.40677	49.408	3.79	849.73	1708.60	0.02	9.13
22000	0.00129	0.00000	50.54908	50.550	3.88	869.38	1748.11	0.02	9.35
22250	0.00132	0.00000	51.70445	51.706	3.97	889.25	1788.06	0.02	9.56
22500	0.00135	0.00000	52.87288	52.874	4.06	909.34	1828.47	0.02	9.78
22750	0.00138	0.00000	54.05436	54.056	4.15	929.66	1869.33	0.02	9.99
23000	0.00141	0.00000	55.24889	55.250	4.24	950.21	1910.64	0.02	10.21
23250	0.00144	0.00000	56.45648	56.458	4.33	970.98	1952.40	0.02	10.44
23500	**0.00147**	**0.00000**	**57.67713**	**57.679**	**4.43**	**991.97**	**1994.61**	**0.02**	**10.66**
23750	0.00150	0.00000	58.91083	58.912	4.52	1013.19	2037.28	0.02	10.89
24000	0.00153	0.00000	60.15758	60.159	4.62	1034.63	2080.39	0.02	11.12
24250	0.00157	0.00000	61.41739	61.419	4.72	1056.30	2123.96	0.02	11.36
24500	0.00160	0.00000	62.69026	62.692	4.81	1078.19	2167.98	0.02	11.59
24750	0.00163	0.00000	63.97618	63.978	4.91	1100.31	2212.45	0.02	11.83
25000	0.00166	0.00000	65.27516	65.277	5.01	1122.65	2257.37	0.02	12.07
25250	0.00170	0.00000	66.58719	66.589	5.11	1145.21	2302.74	0.02	12.31
25500	0.00173	0.00000	67.91227	67.914	5.21	1168.00	2348.57	0.02	12.56

Kinetic Energy Storage: E = K*I*ω^2

where (ω^2) = (w*2*Pi/60)^2)

Shaft Inertia (thick cylinder): I_{shaft} = 0.5*m*(R1^2 +R2^2)

Hub-disk Inertia (thick cylinder): I_{hub} = 0.5*m*(R2^2 +R3^2)

Solid Cylinder Radial Stress: $\sigma_{r\_max} = \sigma_{t\_max} = \rho\omega^2(3-2\upsilon)/8(1-\upsilon))R_4^2$

Hollow Cylinder Radial Stress: $\sigma_{r\_max} = (\rho\omega^2(3-2\upsilon)/8(1-\upsilon))*(R_4^2 - R_3^2)$

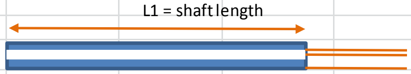
Hollow Cylinder Hoop Stress: $\sigma_{t\_max} = \rho\omega^2/4(1-\upsilon)[(1-2\upsilon)R_3^2 + (3-2\upsilon)R_4^2]$

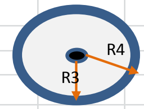
Target Design is >=15% over KWh requirement at break point of 40% and 25% safety factor

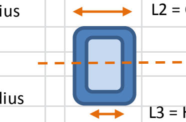
Assume K=0.4 for the solid cylinder flywheel due to radial composit wrap not optimal for radial stress.

Hollow cylinder + hub rotor design with S-Glass composite

Pi =	3.141592654
~1.4 safety factor	
~1.25 safety factor	







Shaft Specifications

0.25	Poisson's Ratio
1950	Shaft material density
2358	Shaft material (MPa)
S-Glass	Shaft Material Description

Hub Specifications

0.25	Poisson's Ratio
1950	Hub & disk material density kg/m^3
2358	Hub & disk MPa tensile strength
S-Glass	Hub & Disk Material Description

Rim Specifications

0.25	Poisson's Ratio
1950	Rim material density (kg/m^3)
2358	Rim MPa tensile strength (MPa)
S-Glass	Hub & Disk Material Description

Design Specifications

0.5	Rim K factor
0.5	Hub disk K factor
0.5	Shaft K factor
0.98	Storage effeciency

Flywheel Specs

1.0291	Shaft length, l1 (m)
0.03	Shaft radius, R2 (m)
0.02	Shaft inner radius, R1 (m)
3.15	Shaft mass (kg)
0.002	Shaft Inertia (kg-m^2)
Rev step	500

0.2150	Hub-Disk Length, L3 (m)
0.0763	Hub-Disk volume (m^3)
148.84	Hub-Disk mass (kg)
7845.51	Hub-disk effective Density (kg/m^3)
8.544	Hub-Disk Inertia (kg-m^2)

450.00	Rim cylinder mass (kg)
0.7500	Cylinder inner diameter (% of radius)
0.2308	Rim structure volume (m^3)
71.19140625	Rim Cylinder Inertia (kg-m^2)
0.3375	Cylinder inner diameter, R3 (m)

50	Energy storage target kWh
0.4500	Rotor Rim Outer Radius, R4 (m)
0.8291	Rotor Rim Cylinder length L2 (m)
601.99	Total Rotor + shaft Mass (kg)
83.06	Watts-hr/kg estimate
0.094792	kWh/liter estimate

Rotor rev/min	Stored Energy (shaft) (kWh)	Stored Energy (Hub) (kWh)	Stored Energy (Cylinder) (kWh)	Total Energy Stored (kWh)	Shaft Hoop or radial Stress (Mpa)	Cylinder Radial Stress (MPa)	Cylinder Hoop Stress (MPa)	Hub-Disk Radial Stress (Mpa)	Hub-Disk Hoop Stress (Mpa)
16000	0.00078	3.26476	27.20310	30.469	8.26	202.08	1027.72	1037.07	108.03
16500	0.00083	3.47200	28.92986	32.403	8.78	214.91	1092.96	1102.90	114.89
17000	0.00088	3.68561	30.70975	34.396	9.32	228.13	1160.20	1170.76	121.96
17500	0.00094	3.90560	32.54277	36.449	9.88	241.75	1229.45	1240.64	129.24
18000	0.00099	4.13197	34.42892	38.562	10.45	255.76	1300.71	1312.55	136.73
18500	0.00105	4.36471	36.36820	40.734	11.04	270.16	1373.98	1386.48	144.43
19000	0.00110	4.60383	38.36062	42.966	11.65	284.96	1449.25	1462.44	152.34
19500	0.00116	4.84932	40.40616	45.257	12.27	300.16	1526.53	1540.42	160.47
20000	0.00122	5.10119	42.50484	47.607	12.91	315.75	1605.82	1620.43	168.80
20500	0.00129	5.35944	44.65665	50.017	13.56	331.74	1687.11	1702.46	177.35
21000	0.00135	5.62407	46.86159	52.487	14.23	348.11	1770.41	1786.52	186.10
21500	0.00141	5.89507	49.11965	55.016	14.91	364.89	1855.72	1872.61	195.07
22000	**0.00148**	**6.17244**	**51.43086**	**57.605**	**15.62**	**382.06**	**1943.04**	**1960.72**	**204.25**
22500	0.00155	6.45620	53.79519	60.253	16.33	399.62	2032.36	2050.85	213.64
23000	0.00162	6.74633	56.21265	62.961	17.07	417.58	2123.69	2143.02	223.24
23500	0.00169	7.04283	58.68324	65.728	17.82	435.93	2217.03	2237.20	233.05
24000	0.00176	7.34572	61.20697	68.554	18.58	454.68	2312.37	2333.42	243.07
24500	0.00184	7.65498	63.78382	71.441	19.37	473.82	2409.73	2431.66	253.31
25000	0.00191	7.97061	66.41381	74.386	20.16	493.36	2509.09	2531.92	263.75
25500	0.00199	8.29263	69.09693	77.392	20.98	513.29	2610.45	2634.21	274.41
26000	0.00207	8.62102	71.83318	80.456	21.81	533.62	2713.83	2738.52	285.27
26500	0.00215	8.95578	74.62256	83.580	22.66	554.34	2819.21	2844.86	296.35
27000	0.00223	9.29692	77.46507	86.764	23.52	575.45	2926.60	2953.23	307.64

Kinetic Energy Storage: E = K*I*ω^2

where (ω^2) = (w*2*Pi/60)^2)

Shaft Inertia (thick cylinder): I_{shaft} = 0.5*m*(R1^2 +R2^2)

Hub-disk Inertia (thick cylinder): I_{hub} = 0.5*m*(R2^2 +R3^2)

Solid Cylinder Radial Stress: $\sigma_{r\_max} = \sigma_{t\_max} = \rho\omega^2(3-2\upsilon)/8(1-\upsilon))R_4^2$

Hollow Cylinder Radial Stress: $\sigma_{r\_max} = \rho\omega^2(3-2\upsilon)/8(1-\upsilon)((R_4^2 - R_3^2)$...

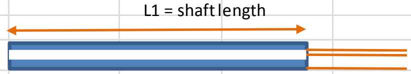
Hollow Cylinder Hoop Stress: $\sigma_{t\_max} = \rho\omega^2/4(1-\upsilon)[(1-2\upsilon)R_3^2 + (3-2\upsilon)R_4^2]$

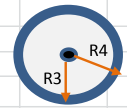
Target Design is >=15% over KWh requirement at break point of 40% and 25% safety factor

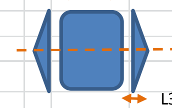
Hub disk composits oriented for radial strength
Cylinder oriented for hoop strength

Reinforced 3-D disk rotor design with S-Glass composite

Pi =	3.141592654
~1.4 safety factor	
~1.25 safety factor	







Shaft Specifications		Overwrap Specifications		Rim Specifications		Design Specifications	
0.25	Poisson's Ratio	0.25	Poisson's Ratio	0.25	Poisson's Ratio	0.8	Rim K factor
1950	Shaft material density	1950	Overwrap material density kg/m^3	1950	Rim material density (kg/m^3)	0.9	Overwrap disk K factor
2358	Shaft material (MPa)	2358	Overwrap MPa tensile strength	2358	Rim MPa tensile strength (MPa)	0.5	Shaft K factor
S-Glass	Shaft Material Description	S-Glass	Overwrap Material Description	S-Glass	Hub & Disk Material Description	0.98	Storage effeciency

Flywheel Specs							
0.8193	Shaft length, l1 (m)	95.00	Overwrap Disk mass, each side (kg)	233.00	Rim cylinder mass (kg)	50	Energy storage target kWh
0.03	Shaft radius, R2 (m)	0.0403	Overwrap volume (m^3)	0.7500	Cylinder inner diameter (% of radius)	0.4500	Rotor Rim Outer Radius, R5 (m)
0.02	Shaft inner radius, R1 (m)	0.09	Overwrap height, L3 (m)	0.1195	Rim structure volume (m^3)	0.4293	Rotor Rim Cylinder Height, L2 (m)
2.51	Shaft mass (kg)	5.771	Overwrap Inertia, each side (kg-m^2)	36.861	Rim Cylinder Inertia (kg-m^2)	425.51	Total Rotor + shaft Mass (kg)
0.002	Shaft Inertia (kg-m^2)	0.018998799	Overwrap top thickness (m)	0.3375	Cylinder inner diameter, R3 (m)	117.51	Watts-hr/kg estimate
Rev step:	500	4070.65	Effective Density (kg/m^3)	0.4310	Cylinder outer diameter, R4 (m)	0.141367	kWh/liter estimate

Rotor rev/min	Stored Energy (shaft) kWh	Stored Energy (Overwrap) (kWh)	Stored Energy (Cylinder) (kWh)	Total Energy Stored (kWh)	Shaft Hoop or radial Stress (Mpa)	Cylinder Radial Stress (MPa)	Cylinder Hoop Stress (MPa)	Overwrap Radial Stress (Mpa)	Overwrap Hoop Stress (Mpa)
16000	0.00062	7.93895	22.53625	30.476	4.29	163.90	951.36	959.93	1027.72
16500	0.00066	8.44289	23.96678	32.410	4.56	174.31	1011.75	1020.87	1092.96
17000	0.00070	8.96233	25.44132	34.404	4.84	185.03	1074.00	1083.67	1160.20
17500	0.00075	9.49728	26.95987	36.458	5.13	196.07	1138.11	1148.36	1229.45
18000	0.00079	10.04774	28.52245	38.571	5.42	207.44	1204.07	1214.91	1300.71
18500	0.00083	10.61370	30.12904	40.744	5.73	219.12	1271.89	1283.35	1373.98
19000	0.00088	11.19516	31.77964	42.976	6.04	231.13	1341.57	1353.65	1449.25
19500	0.00093	11.79213	33.47426	45.267	6.37	243.45	1413.11	1425.84	1526.53
20000	0.00097	12.40461	35.21290	47.618	6.70	256.10	1486.51	1499.89	1605.82
20500	0.00102	13.03260	36.99555	50.029	7.03	269.06	1561.76	1575.83	1687.11
21000	0.00107	13.67609	38.82222	52.499	7.38	282.35	1638.87	1653.63	1770.41
21500	0.00113	14.33508	40.69291	55.029	7.74	295.95	1717.84	1733.31	1855.72
22000	**0.00118**	**15.00958**	**42.60761**	**57.618**	**8.10**	**309.88**	**1798.67**	**1814.87**	**1943.04**
22500	0.00123	15.69959	44.56632	60.267	8.47	324.12	1881.36	1898.30	2032.36
23000	0.00129	16.40510	46.56906	62.975	8.86	338.69	1965.90	1983.61	2123.69
23500	0.00134	17.12612	48.61581	65.743	9.24	353.57	2052.31	2070.79	2217.03
24000	0.00140	17.86264	50.70657	68.571	9.64	368.78	2140.57	2159.85	2312.37
24500	0.00146	18.61467	52.84135	71.457	10.05	384.30	2230.69	2250.78	2409.73
25000	0.00152	19.38221	55.02015	74.404	10.46	400.15	2322.67	2343.58	2509.09
25500	0.00158	20.16525	57.24297	77.410	10.89	416.32	2416.50	2438.27	2610.45
26000	0.00165	20.96379	59.50980	80.475	11.32	432.80	2512.20	2534.82	2713.83
26500	0.00171	21.77785	61.82064	83.600	11.76	449.61	2609.75	2633.25	2819.21
27000	0.00177	22.60741	64.17551	86.785	12.20	466.73	2709.16	2733.56	2926.60

Kinetic Energy Storage: E = K*I*ω^2

where (ω^2) = (w*2*Pi/60)^2)

Shaft Inertia (thick cylinder): I_{shaft} = 0.5*m*(R1^2 +R2^2)

Hub-disk Inertia (thick cylinder): I_{hub} = 0.5*m*(R2^2 +R3^2)

Conical disk interia: $I_{overwrap}$ = 3/10*m*R4^2

Solid Cylinder Radial Stress: $\sigma_{r\_max} = \sigma_{t\_max} = \rho\omega^2(3-2\upsilon)/8(1-\upsilon))R_4^2$

Hollow Cylinder Radial Stress: $\sigma_{r\_max} = \rho\omega^2(3-2\upsilon)/8(1-\upsilon)((R_4^2 - R_3^2)$...

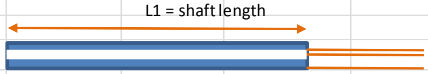
Hollow Cylinder Hoop Stress: $\sigma_{t\_max} = \rho\omega^2/4(1-\upsilon)[(1-2\upsilon)R_3^2 + (3-2\upsilon)R_4^2]$

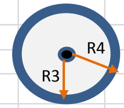
Target Design is >=15% over KWh requirement at break point of 40% and 25% safety factor

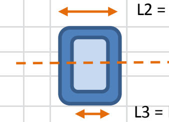
Assume K=0.8 for the advanced flywheel while using the Cylinder stress equations since complex toroidal stress analysis equations are unavailable. Overwrap modeled as a conical disk with an added thickness to the overwrap cylinder to take axial loads along composite fiber strength (K=0.9)

Solid cylinder rotor design with AS4C Composite

Pi =	3.141592654
~1.4 safety factor	
~1.25 safety factor	







Shaft Specifications

0.25	Poisson's Ratio
1470	Shaft material density
2206	Shaft material (MPa)
AS4C	Shaft Material Description

Hub Specifications

0.25	Poisson's Ratio
1470	Hub & disk material density kg/m^3
2206	Hub & disk MPa tensile strength
AS4C	Hub & Disk Material Description

Rim Specifications

0.25	Poisson's Ratio
1470	Rim material density (kg/m^3)
2206	Rim MPa tensile strength (MPa)
AS4C	Hub & Disk Material Description

Design Specifications

0.4	Rim K factor
0	Hub disk K factor
0.5	Shaft K factor
0.98	Storage effeciency

Flywheel Specs

0.9530	Shaft length, l1 (m)	0.0000	Hub-Disk Length, L3 (m)	701.00	Rim cylinder mass (kg)	50	Energy storage target kWh
0.03	Shaft radius, R2 (m)	0.0000	Hub-Disk volume (m^3)	0.0668	Cylinder inner diameter (% of radius)	0.4500	Rotor Rim Outer Radius, R4 (m)
0.02	Shaft inner radius, R1 (m)	0.00	Hub-Disk mass (kg)	0.4769	Rim structure volume (m^3)	0.7530	Rotor Rim Cylinder Height, L2 (m)
2.20	Shaft mass (kg)	1470.00	Hub-disk effective Density (kg/m^3)	71.29296306	Rim Cylinder Inertia (kg-m^2)	703.20	Total Rotor + shaft Mass (kg)
0.001	Shaft Inertia (kg-m^2)	0.000	Hub-Disk Inertia (kg-m^2)	0.03006	Cylinder inner diameter, R3 (m)	71.10	Watts-hr/kg estimate
Rev step	500					0.104382	kWh/liter estimate

Rotor rev/min	Stored Energy (shaft) (kWh)	Stored Energy (Hub) (kWh)	Stored Energy (Cylinder) (kWh)	Total Energy Stored (kWh)	Shaft Hoop or radial Stress est. (Mpa)	Cylinder Radial Stress (MPa)	Cylinder Hoop Stress (MPa)	Hub-Disk Radial Stress (Mpa)	Hub-Disk Hoop Stress (Mpa)
20000	0.00085	0.00000	34.05238	34.053	2.42	541.63	1089.09	0.01	5.82
20500	0.00090	0.00000	35.77628	35.777	2.54	569.05	1144.23	0.01	6.12
21000	0.00094	0.00000	37.54275	37.544	2.67	597.15	1200.73	0.01	6.42
21500	0.00099	0.00000	39.35178	39.353	2.79	625.93	1258.59	0.01	6.73
22000	0.00103	0.00000	41.20338	41.204	2.93	655.38	1317.80	0.01	7.05
22500	0.00108	0.00000	43.09754	43.099	3.06	685.51	1378.39	0.01	7.37
23000	0.00113	0.00000	45.03427	45.035	3.20	716.31	1440.33	0.01	7.70
23500	0.00118	0.00000	47.01357	47.015	3.34	747.79	1503.63	0.01	8.04
24000	0.00123	0.00000	49.03543	49.037	3.48	779.95	1568.30	0.01	8.38
24500	0.00128	0.00000	51.09985	51.101	3.63	812.79	1634.32	0.01	8.74
25000	0.00133	0.00000	53.20684	53.208	3.78	846.30	1701.71	0.02	9.10
25500	0.00139	0.00000	55.35640	55.358	3.93	880.49	1770.46	0.02	9.47
26000	**0.00144**	**0.00000**	**57.54852**	**57.550**	**4.09**	**915.36**	**1840.57**	**0.02**	**9.84**
26500	0.00150	0.00000	59.78321	59.785	4.25	950.91	1912.04	0.02	10.22
27000	0.00156	0.00000	62.06046	62.062	4.41	987.13	1984.88	0.02	10.61
27500	0.00161	0.00000	64.38028	64.382	4.57	1024.03	2059.07	0.02	11.01
28000	0.00167	0.00000	66.74266	66.744	4.74	1061.60	2134.63	0.02	11.41
28500	0.00173	0.00000	69.14761	69.149	4.91	1099.86	2211.54	0.02	11.82
29000	0.00180	0.00000	71.59513	71.597	5.08	1138.79	2289.82	0.02	12.24
29500	0.00186	0.00000	74.08521	74.087	5.26	1178.39	2369.46	0.02	12.67
30000	0.00192	0.00000	76.61785	76.620	5.44	1218.68	2450.46	0.02	13.10
30500	0.00199	0.00000	79.19306	79.195	5.62	1259.64	2532.83	0.02	13.54
31000	0.00205	0.00000	81.81084	81.813	5.81	1301.28	2616.55	0.02	13.99

Kinetic Energy Storage: E = K*I*ω^2

where (ω^2) = (w*2*Pi/60)^2)

Shaft Inertia (thick cylinder): I_{shaft} = 0.5*m*(R1^2 +R2^2)

Hub-disk Inertia (thick cylinder): I_{hub} = 0.5*m*(R2^2 +R3^2)

Solid Cylinder Radial Stress: $\sigma_{r\_max} = \sigma_{t\_max} = \rho\omega^2(3-2\upsilon)/8(1-\upsilon))R_4^2$

Hollow Cylinder Radial Stress: $\sigma_{r\_max} = (\rho\omega^2(3-2\upsilon)/8(1-\upsilon))*(R_4^2 - R_3^2)$

Hollow Cylinder Hoop Stress: $\sigma_{t\_max} = \rho\omega^2/4(1-\upsilon)[(1-2\upsilon)R_3^2 + (3-2\upsilon)R_4^2]$

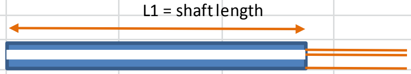
Target Design is >=15% over KWh requirement at break point of 40% and 25% safety factor

Assume K=0.4 for the solid cylinder flywheel due to radial composit wrap not optimal for radial stress.

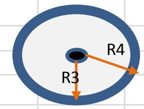
Hollow cylinder + hub rotor design with AS4C Composite

Pi =	3.141592654
~1.4 safety factor	
~1.25 safety factor	

L1 = shaft length

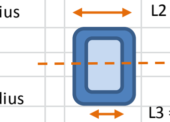


R1 = inner shaft radius
R2 = outer shaft radius



R3 = Cyclinder Inner Radius
R4 = Cyclinder Outer Radius

L2 = Cyclinder length



L3 = Hub length

Shaft Specifications		Hub Specifications		Rim Specifications		Design Specifications	
0.25	Poisson's Ratio	0.25	Poisson's Ratio	0.25	Poisson's Ratio	0.5	Rim K factor
1470	Shaft material density	1470	Hub & disk material density kg/m^3	1470	Rim material density (kg/m^3)	0.5	Hub disk K factor
2206	Shaft material (MPa)	2206	Hub & disk MPa tensile strength	2206	Rim MPa tensile strength (MPa)	0.5	Shaft K factor
AS4C	Shaft Material Description	AS4C	Hub & Disk Material Description	AS4C	Hub & Disk Material Description	0.98	Storage effeciency

Flywheel Specs							
1.0897	Shaft length, l1 (m)	0.2250	Hub-Disk Length, L3 (m)	364.00	Rim cylinder mass (kg)	50	Energy storage target kWh
0.03	Shaft radius, R2 (m)	0.0799	Hub-Disk volume (m^3)	0.7500	Cylinder inner diameter (% of radius)	0.4500	Rotor Rim Outer Radius, R4 (m)
0.02	Shaft inner radius, R1 (m)	117.42	Hub-Disk mass (kg)	0.2476	Rim structure volume (m^3)	0.8897	Rotor Rim Cylinder length L2 (m)
2.52	Shaft mass (kg)	6026.87	Hub-disk effective Density (kg/m^3)	57.5859375	Rim Cylinder Inertia (kg-m^2)	483.94	Total Rotor + shaft Mass (kg)
0.002	Shaft Inertia (kg-m^2)	6.740	Hub-Disk Inertia (kg-m^2)	0.3375	Cylinder inner diameter, R3 (m)	103.32	Watts-hr/kg estimate
Rev step	500					0.088341	kWh/liter estimate

Rotor rev/min	Stored Energy (shaft) (kWh)	Stored Energy (Hub) (kWh)	Stored Energy (Cylinder) (kWh)	Total Energy Stored (kWh)	Shaft Hoop or radial Stress (Mpa)	Cylinder Radial Stress (MPa)	Cylinder Hoop Stress (MPa)	Hub-Disk Radial Stress (Mpa)	Hub-Disk Hoop Stress (Mpa)
18000	0.00079	3.25974	27.84917	31.110	8.03	192.80	980.54	1008.29	103.07
18500	0.00084	3.44336	29.41784	32.862	8.48	203.66	1035.77	1065.08	108.88
19000	0.00088	3.63200	31.02948	34.662	8.95	214.82	1092.51	1123.43	114.84
19500	0.00093	3.82567	32.68410	36.511	9.42	226.27	1150.77	1183.34	120.97
20000	0.00098	4.02438	34.38169	38.407	9.91	238.03	1210.54	1244.80	127.25
20500	0.00103	4.22811	36.12227	40.351	10.42	250.08	1271.82	1307.82	133.69
21000	0.00108	4.43687	37.90582	42.344	10.93	262.42	1334.62	1372.39	140.29
21500	0.00113	4.65067	39.73234	44.384	11.46	275.07	1398.93	1438.52	147.05
22000	0.00118	4.86949	41.60185	46.473	12.00	288.01	1464.75	1506.21	153.97
22500	0.00124	5.09335	43.51433	48.609	12.55	301.25	1532.09	1575.45	161.05
23000	0.00129	5.32224	45.46979	50.793	13.11	314.79	1600.94	1646.25	168.29
23500	0.00135	5.55615	47.46822	53.026	13.69	328.63	1671.30	1718.60	175.68
24000	0.00141	5.79510	49.50964	55.306	14.28	342.76	1743.17	1792.51	183.24
24500	**0.00147**	**6.03908**	**51.59403**	**57.635**	**14.88**	**357.19**	**1816.56**	**1867.98**	**190.95**
25000	0.00153	6.28809	53.72139	60.011	15.49	371.92	1891.47	1945.00	198.83
25500	0.00159	6.54213	55.89174	62.435	16.12	386.94	1967.88	2023.58	206.86
26000	0.00165	6.80120	58.10506	64.908	16.75	402.27	2045.81	2103.71	215.05
26500	0.00171	7.06529	60.36136	67.428	17.40	417.89	2125.25	2185.41	223.40
27000	0.00178	7.33442	62.66063	69.997	18.07	433.80	2206.21	2268.65	231.91
27500	0.00185	7.60859	65.00289	72.613	18.74	450.02	2288.67	2353.45	240.58
28000	0.00191	7.88778	67.38812	75.278	19.43	466.53	2372.65	2439.81	249.41
28500	0.00198	8.17200	69.81632	77.990	20.13	483.34	2458.15	2527.73	258.40
29000	0.00205	8.46125	72.28751	80.751	20.84	500.45	2545.16	2617.20	267.54

Kinetic Energy Storage: E = K*I*ω^2
where (ω^2) = (w*2*Pi/60)^2)

Shaft Inertia (thick cylinder): I_{shaft} = 0.5*m*(R1^2 +R2^2)

Hub-disk Inertia (thick cylinder): I_{hub} = 0.5*m*(R2^2 +R3^2)

Solid Cylinder Radial Stress: $\sigma_{r\_max} = \sigma_{t\_max} = \rho\omega^2(3-2\upsilon)/8(1-\upsilon))R_4^2$

Hollow Cylinder Radial Stress: $\sigma_{r\_max} = \rho\omega^2(3-2\upsilon)/8(1-\upsilon)((R_4^2 - R_3^2)$...

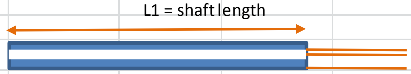
Hollow Cylinder Hoop Stress: $\sigma_{t\_max} = \rho\omega^2/4(1-\upsilon)[(1-2\upsilon)R_3^2 + (3-2\upsilon)R_4^2]$

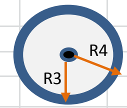
Target Design is >=15% over KWh requirement at break point of 40% and 25% safety factor

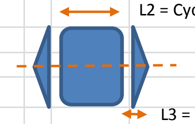
Hub disk composits oriented for radial strength
Cylinder oriented for hoop strength

Reinforced 3-D disk rotor design with AS4C Composite

Pi =	3.141592654
~1.4 safety factor	
~1.25 safety factor	







Shaft Specifications

0.25	Poisson's Ratio
1470	Shaft material density
2206	Shaft material (MPa)
AS4C	Shaft Material Description

Overwrap Specifications

0.25	Poisson's Ratio
1470	Overwrap material density kg/m^3
2206	Overwrap MPa tensile strength
AS4C	Overwrap Material Description

Rim Specifications

0.25	Poisson's Ratio
1470	Rim material density (kg/m^3)
2206	Rim MPa tensile strength (MPa)
AS4C	Hub & Disk Material Description

Design Specifications

0.8	Rim K factor
0.9	Overwrap disk K factor
0.5	Shaft K factor
0.98	Storage effeciency

Flywheel Specs

0.8226	Shaft length, l1 (m)	90.00	Overwrap Disk mass, each side (kg)	176.00	Rim cylinder mass (kg)	50	Energy storage target kWh
0.03	Shaft radius, R2 (m)	0.0408	Overwrap volume (m^3)	0.7500	Cylinder inner diameter (% of radius)	0.4500	Rotor Rim Outer Radius, R5 (m)
0.02	Shaft inner radius, R1 (m)	0.10	Overwrap height, L3 (m)	0.1197	Rim structure volume (m^3)	0.4302	Rotor Rim Cylinder Height, L2 (m)
1.90	Shaft mass (kg)	5.468	Overwrap Inertia, each side (kg-m^2)	27.844	Rim Cylinder Inertia (kg-m^2)	357.90	Total Rotor + shaft Mass (kg)
0.001	Shaft Inertia (kg-m^2)	0.019239038	Overwrap top thickness (m)	0.3375	Cylinder inner diameter, R3 (m)	139.70	Watts-hr/kg estimate
Rev step:	500	3259.98	Effective Density (kg/m^3)	0.4308	Cylinder outer diameter, R4 (m)	0.140742	kWh/liter estimate

Rotor rev/min	Stored Energy (shaft) kWh	Stored Energy (Overwrap) (kWh)	Stored Energy (Cylinder) (kWh)	Total Energy Stored (kWh)	Shaft Hoop or radial Stress (Mpa)	Cylinder Radial Stress (MPa)	Cylinder Hoop Stress (MPa)	Overwrap Radial Stress (Mpa)	Overwrap Hoop Stress (Mpa)
20000	0.00074	11.75174	26.59858	38.351	5.36	192.50	1119.48	1201.19	1210.54
20500	0.00077	12.34667	27.94514	40.293	5.63	202.25	1176.16	1262.00	1271.82
21000	0.00081	12.95629	29.32494	42.282	5.91	212.23	1234.23	1324.31	1334.62
21500	0.00085	13.58060	30.73799	44.319	6.20	222.46	1293.70	1388.12	1398.93
22000	0.00089	14.21960	32.18429	46.405	6.49	232.93	1354.58	1453.44	1464.75
22500	0.00093	14.87329	33.66383	48.538	6.79	243.63	1416.85	1520.25	1532.09
23000	0.00097	15.54167	35.17663	50.719	7.09	254.58	1480.52	1588.57	1600.94
23500	0.00102	16.22474	36.72267	52.948	7.40	265.77	1545.59	1658.39	1671.30
24000	0.00106	16.92250	38.30196	55.226	7.72	277.20	1612.06	1729.71	1743.17
24500	**0.00111**	**17.63495**	**39.91450**	**57.551**	**8.05**	**288.87**	**1679.93**	**1802.53**	**1816.56**
25000	0.00115	18.36209	41.56029	59.924	8.38	300.78	1749.19	1876.86	1891.47
25500	0.00120	19.10392	43.23932	62.344	8.72	312.93	1819.86	1952.68	1967.88
26000	0.00125	19.86044	44.95161	64.813	9.06	325.33	1891.93	2030.01	2045.81
26500	0.00129	20.63164	46.69714	67.330	9.41	337.96	1965.40	2108.84	2125.25
27000	0.00134	21.41754	48.47592	69.895	9.77	350.83	2040.26	2189.17	2206.21
27500	0.00139	22.21813	50.28795	72.507	10.14	363.95	2116.53	2271.00	2288.67
28000	0.00144	23.03341	52.13322	75.168	10.51	377.30	2194.19	2354.33	2372.65
28500	0.00150	23.86337	54.01175	77.877	10.89	390.90	2273.25	2439.16	2458.15
29000	0.00155	24.70803	55.92352	80.633	11.27	404.73	2353.72	2525.50	2545.16
29500	0.00160	25.56737	57.86854	83.438	11.67	418.81	2435.58	2613.34	2633.68
30000	0.00166	26.44141	59.84681	86.290	12.07	433.13	2518.84	2702.67	2723.71
30500	0.00171	27.33014	61.85833	89.190	12.47	447.68	2603.50	2793.51	2815.26
31000	0.00177	28.23355	63.90310	92.138	12.88	462.48	2689.56	2885.86	2908.32

Kinetic Energy Storage: E = K*I*ω^2
where (ω^2) = (w*2*Pi/60)^2)

Shaft Inertia (thick cylinder): I_{shaft} = 0.5*m*(R1^2 +R2^2)

Hub-disk Inertia (thick cylinder): I_{hub} = 0.5*m*(R2^2 +R3^2)

Conical disk interia: $I_{overwrap}$ = 3/10*m*R4^2

Solid Cylinder Radial Stress: $\sigma_{r\_max} = \sigma_{t\_max} = \rho\omega^2(3-2\upsilon)/8(1-\upsilon))R_4^2$

Hollow Cylinder Radial Stress: $\sigma_{r\_max} = \rho\omega^2(3-2\upsilon)/8(1-\upsilon)((R_4^2 - R_3^2)$...

Hollow Cylinder Hoop Stress: $\sigma_{t\_max} = \rho\omega^2/4(1-\upsilon)[(1-2\upsilon)R_3^2 + (3-2\upsilon)R_4^2]$

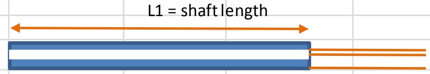
Target Design is >=15% over KWh requirement at break point of 40% and 25% safety factor

Assume K=0.8 for the advanced flywheel while using the Cylinder stress equations since complex toroidal stress analysis equations are unavailable. Overwrap modeled as a conical disk with an added thickness to the overwrap cylinder to take axial loads along composite fiber strength (K=0.9)

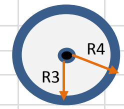
Solid cylinder rotor design with IM10 Composite

Pi =	3.141592654
~1.4 safety factor	
~1.25 safety factor	

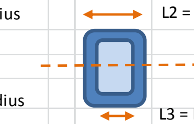
L1 = shaft length



R1 = inner shaft radius
R2 = outer shaft radius



R3 = Cycinder Inner Radius
R4 = Cycinder Outer Radius



L2 = Cyclinder length
L3 = Hub length

Shaft Specifications		**Hub Specifications**		**Rim Specifications**		**Design Specifications**	
0.25	Poisson's Ratio	0.25	Poisson's Ratio	0.25	Poisson's Ratio	0.4	Rim K factor
1470	Shaft material density	1470	Hub & disk material density kg/m^3	1470	Rim material density (kg/m^3)	0	Hub disk K factor
3310	Shaft material (MPa)	3310	Hub & disk MPa tensile strength	3310	Rim MPa tensile strength (MPa)	0.5	Shaft K factor
IM10	Shaft Material Description	IM10	Hub & Disk Material Description	IM10	Hub & Disk Material Description	0.98	Storage effeciency

Flywheel Specs							
0.6973	Shaft length, l1 (m)	0.0000	Hub-Disk Length, L3 (m)	463.00	Rim cylinder mass (kg)	50	Energy storage target kWh
0.03	Shaft radius, R2 (m)	0.0000	Hub-Disk volume (m^3)	0.0668	Cylinder inner diameter (% of radius)	0.4500	Rotor Rim Outer Radius, R4 (m)
0.02	Shaft inner radius, R1 (m)	0.00	Hub-Disk mass (kg)	0.3150	Rim structure volume (m^3)	0.4973	Rotor Rim Cylinder Height, L2 (m)
1.61	Shaft mass (kg)	1470.00	Hub-disk effective Density (kg/m^3)	47.08793423	Rim Cylinder Inertia (kg-m^2)	464.61	Total Rotor + shaft Mass (kg)
0.001	Shaft Inertia (kg-m^2)	0.000	Hub-Disk Inertia (kg-m^2)	0.03006	Cylinder inner diameter, R3 (m)	107.62	Watts-hr/kg estimate
Rev step	500					0.158039	kWh/liter estimate

Rotor rev/min	Stored Energy (shaft) (kWh)	Stored Energy (Hub) (kWh)	Stored Energy (Cylinder) (kWh)	Total Energy Stored (kWh)	Shaft Hoop or radial Stress est. (Mpa)	Cylinder Radial Stress (MPa)	Cylinder Hoop Stress (MPa)	Hub-Disk Radial Stress (Mpa)	Hub-Disk Hoop Stress (Mpa)
25000	0.00098	0.00000	35.14232	35.143	3.78	846.30	1701.71	0.02	9.10
25500	0.00102	0.00000	36.56207	36.563	3.93	880.49	1770.46	0.02	9.47
26000	0.00106	0.00000	38.00994	38.011	4.09	915.36	1840.57	0.02	9.84
26500	0.00110	0.00000	39.48591	39.487	4.25	950.91	1912.04	0.02	10.22
27000	0.00114	0.00000	40.99000	40.991	4.41	987.13	1984.88	0.02	10.61
27500	0.00118	0.00000	42.52221	42.523	4.57	1024.03	2059.07	0.02	11.01
28000	0.00122	0.00000	44.08253	44.084	4.74	1061.60	2134.63	0.02	11.41
28500	0.00127	0.00000	45.67096	45.672	4.91	1099.86	2211.54	0.02	11.82
29000	0.00131	0.00000	47.28751	47.289	5.08	1138.79	2289.82	0.02	12.24
29500	0.00136	0.00000	48.93217	48.934	5.26	1178.39	2369.46	0.02	12.67
30000	0.00141	0.00000	50.60494	50.606	5.44	1218.68	2450.46	0.02	13.10
30500	0.00145	0.00000	52.30583	52.307	5.62	1259.64	2532.83	0.02	13.54
31000	0.00150	0.00000	54.03483	54.036	5.81	1301.28	2616.55	0.02	13.99
31500	0.00155	0.00000	55.79195	55.794	6.00	1343.59	2701.64	0.02	14.44
32000	**0.00160**	**0.00000**	**57.57718**	**57.579**	**6.19**	**1386.58**	**2788.08**	**0.02**	**14.91**
32500	0.00165	0.00000	59.39052	59.392	6.39	1430.25	2875.89	0.03	15.38
33000	0.00170	0.00000	61.23198	61.234	6.58	1474.60	2965.06	0.03	15.85
33500	0.00175	0.00000	63.10155	63.103	6.78	1519.62	3055.59	0.03	16.34
34000	0.00181	0.00000	64.99924	65.001	6.99	1565.32	3147.48	0.03	16.83
34500	0.00186	0.00000	66.92504	66.927	7.20	1611.70	3240.74	0.03	17.33
35000	0.00191	0.00000	68.87895	68.881	7.41	1658.75	3335.35	0.03	17.83
35500	0.00197	0.00000	70.86098	70.863	7.62	1706.49	3431.33	0.03	18.35
36000	0.00202	0.00000	72.87112	72.873	7.83	1754.89	3528.67	0.03	18.87

Kinetic Energy Storage: E = K*I*ω^2

where (ω^2) = (w*2*Pi/60)^2)

Shaft Inertia (thick cylinder): I_{shaft} = 0.5*m*(R1^2 +R2^2)

Hub-disk Inertia (thick cylinder): I_{hub} = 0.5*m*(R2^2 +R3^2)

Solid Cylinder Radial Stress: $\sigma_{r\_max} = \sigma_{t\_max} = \rho\omega^2(3-2\upsilon)/8(1-\upsilon))R_4^2$

Hollow Cylinder Radial Stress: $\sigma_{r\_max} = (\rho\omega^2(3-2\upsilon)/8(1-\upsilon))*(R_4^2 - R_3^2)$

Hollow Cylinder Hoop Stress: $\sigma_{t\_max} = \rho\omega^2/4(1-\upsilon)\,[(1-2\upsilon)R_3^2 + (3-2\upsilon)R_4^2]$

Target Design is >=15% over KWh requirement at break point of 40% and 25% safety factor

Assume K=0.4 for the solid cylinder flywheel due to radial composit wrap not optimal for radial stress.

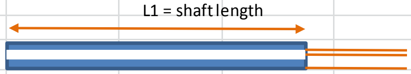
Hollow cylinder + hub rotor design with IM10 Composite

Pi =	3.141592654

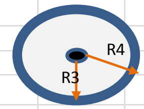
~1.4 safety factor

~1.25 safety factor

L1 = shaft length

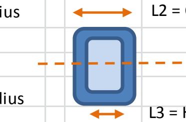


R1 = inner shaft radius
R2 = outer shaft radius



R3 = Cyclinder Inner Radius

R4 = Cyclinder Outer Radius



L2 = Cyclinder length

L3 = Hub length

Shaft Specifications		Hub Specifications		Rim Specifications		Design Specifications	
0.25	Poisson's Ratio	0.25	Poisson's Ratio	0.25	Poisson's Ratio	0.5	Rim K factor
1470	Shaft material density	1470	Hub & disk material density kg/m^3	1470	Rim material density (kg/m^3)	0.5	Hub disk K factor
3310	Shaft material (MPa)	3310	Hub & disk MPa tensile strength	3310	Rim MPa tensile strength (MPa)	0.5	Shaft K factor
IM10	Shaft Material Description	IM10	Hub & Disk Material Description	IM10	Hub & Disk Material Description	0.98	Storage effeciency

Flywheel Specs							
0.7939	Shaft length, l1 (m)	0.1500	Hub-Disk Length, L3 (m)	243.00	Rim cylinder mass (kg)	50	Energy storage target kWh
0.03	Shaft radius, R2 (m)	0.0533	Hub-Disk volume (m^3)	0.7500	Cylinder inner diameter (% of radius)	0.4500	Rotor Rim Outer Radius, R4 (m)
0.02	Shaft inner radius, R1 (m)	78.28	Hub-Disk mass (kg)	0.1653	Rim structure volume (m^3)	0.5939	Rotor Rim Cylinder length L2 (m)
1.83	Shaft mass (kg)	6033.13	Hub-disk effective Density (kg/m^3)	38.44335938	Rim Cylinder Inertia (kg-m^2)	323.12	Total Rotor + shaft Mass (kg)
0.001	Shaft Inertia (kg-m^2)	4.494	Hub-Disk Inertia (kg-m^2)	0.3375	Cylinder inner diameter, R3 (m)	154.74	Watts-hr/kg estimate
Rev step	500					0.13233	kWh/liter estimate

Rotor rev/min	Stored Energy (shaft) (kWh)	Stored Energy (Hub) (kWh)	Stored Energy (Cylinder) (kWh)	Total Energy Stored (kWh)	Shaft Hoop or radial Stress (Mpa)	Cylinder Radial Stress (MPa)	Cylinder Hoop Stress (MPa)	Hub-Disk Radial Stress (Mpa)	Hub-Disk Hoop Stress (Mpa)
22000	0.00086	3.24633	27.77266	31.020	12.01	288.01	1464.75	1507.77	153.97
22500	0.00090	3.39557	29.04940	32.446	12.56	301.25	1532.09	1577.09	161.05
23000	0.00094	3.54816	30.35483	33.904	13.12	314.79	1600.94	1647.96	168.29
23500	0.00098	3.70410	31.68895	35.394	13.70	328.63	1671.30	1720.39	175.68
24000	0.00102	3.86340	33.05176	36.916	14.29	342.76	1743.17	1794.38	183.24
24500	0.00107	4.02605	34.44327	38.470	14.89	357.19	1816.56	1869.92	190.95
25000	0.00111	4.19206	35.86346	40.057	15.51	371.92	1891.47	1947.02	198.83
25500	0.00116	4.36142	37.31234	41.675	16.13	386.94	1967.88	2025.68	206.86
26000	0.00120	4.53413	38.78992	43.325	16.77	402.27	2045.81	2105.90	215.05
26500	0.00125	4.71020	40.29618	45.008	17.42	417.89	2125.25	2187.67	223.40
27000	0.00130	4.88962	41.83114	46.722	18.09	433.80	2206.21	2271.01	231.91
27500	0.00135	5.07239	43.39478	48.469	18.76	450.02	2288.67	2355.90	240.58
28000	0.00139	5.25852	44.98712	50.247	19.45	466.53	2372.65	2442.35	249.41
28500	0.00144	5.44800	46.60815	52.058	20.15	483.34	2458.15	2530.35	258.40
29000	0.00150	5.64083	48.25787	53.900	20.87	500.45	2545.16	2619.91	267.54
29500	0.00155	5.83702	49.93628	55.775	21.59	517.86	2633.68	2711.03	276.85
30000	**0.00160**	**6.03656**	**51.64338**	**57.682**	**22.33**	**535.56**	**2723.71**	**2803.71**	**286.31**
30500	0.00165	6.23946	53.37917	59.620	23.08	553.56	2815.26	2897.95	295.94
31000	0.00171	6.44571	55.14365	61.591	23.84	571.86	2908.32	2993.74	305.72
31500	0.00176	6.65531	56.93683	63.594	24.62	590.46	3002.89	3091.09	315.66
32000	0.00182	6.86827	58.75869	65.629	25.41	609.35	3098.98	3190.00	325.76
32500	0.00188	7.08458	60.60924	67.696	26.21	628.54	3196.58	3290.47	336.02
33000	0.00194	7.30424	62.48849	69.795	27.02	648.03	3295.69	3392.49	346.44

Kinetic Energy Storage: E = K*I*ω^2

where (ω^2) = (w*2*Pi/60)^2)

Shaft Inertia (thick cylinder): I_{shaft} = 0.5*m*(R1^2 +R2^2)

Hub-disk Inertia (thick cylinder): I_{hub} = 0.5*m*(R2^2 +R3^2)

Solid Cylinder Radial Stress: $\sigma_{r\_max} = \sigma_{t\_max} = \rho\omega^2(3- 2\upsilon) /8(1-\upsilon))R_4^2$

Hollow Cylinder Radial Stress: $\sigma_{r\_max} = \rho\omega^2(3- 2\upsilon) /8(1-\upsilon) ((R_4^2 - R_3^2)$...

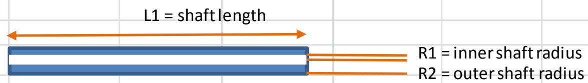
Hollow Cylinder Hoop Stress: $\sigma_{t\_max} = \rho\omega^2 /4(1-\upsilon) [(1 - 2\upsilon)R_3^2 + (3- 2\upsilon)R_4^2]$

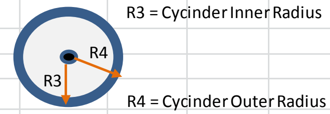
Target Design is >=15% over KWh requirement at break point of 40% and 25% safety factor

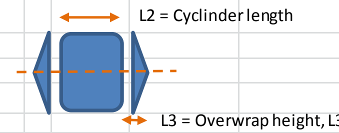
Hub disk composits oriented for radial strength
Cylinder oriented for hoop strength

Reinforced 3-D disk rotor design with IM10 Composite

Pi =	3.141592654
~1.4 safety factor	
~1.25 safety factor	







Shaft Specifications

0.25	Poisson's Ratio
1470	Shaft material density
3310	Shaft material (MPa)
IM10	Shaft Material Description

Overwrap Specifications

0.25	Poisson's Ratio
1470	Overwrap material density kg/m^3
3310	Overwrap MPa tensile strength
IM10	Overwrap Material Description

Rim Specifications

0.25	Poisson's Ratio
1470	Rim material density (kg/m^3)
3310	Rim MPa tensile strength (MPa)
IM10	Hub & Disk Material Description

Design Specifications

0.8	Rim K factor
0.9	Overwrap disk K factor
0.5	Shaft K factor
0.98	Storage effeciency

Flywheel Specs

0.5531	Shaft length, l1 (m)
0.03	Shaft radius, R2 (m)
0.02	Shaft inner radius, R1 (m)
1.28	Shaft mass (kg)
0.001	Shaft Inertia (kg-m^2)
Rev step:	500

90.00	Overwrap Disk mass, each side (kg)
0.0272	Overwrap volume (m^3)
0.06	Overwrap height, L3 (m)
5.468	Overwrap Inertia, each side (kg-m^2)
0.012822151	Overwrap top thickness (m)
3346.78	Effective Density (kg/m^3)

92.00	Rim cylinder mass (kg)
0.7500	Cylinder inner diameter (% of radius)
0.0626	Rim structure volume (m^3)
14.555	Rim Cylinder Inertia (kg-m^2)
0.3375	Cylinder inner diameter, R3 (m)
0.4372	Cylinder outer diameter, R4 (m)

50	Energy storage target kWh
0.4500	Rotor Rim Outer Radius, R5 (m)
0.2249	Rotor Rim Cylinder Height, L2 (m)
273.28	Total Rotor + shaft Mass (kg)
182.96	Watts-hr/kg estimate
0.253252	kWh/liter estimate

Rotor rev/min	Stored Energy (shaft) kWh	Stored Energy (Overwrap) (kWh)	Stored Energy (Cylinder) (kWh)	Total Energy Stored (kWh)	Shaft Hoop or radial Stress (Mpa)	Cylinder Radial Stress (MPa)	Cylinder Hoop Stress (MPa)	Overwrap Radial Stress (Mpa)	Overwrap Hoop Stress (Mpa)
22000	0.00060	14.21960	16.82360	31.044	6.66	251.03	1390.79	1492.14	1464.75
22500	0.00063	14.87329	17.59700	32.471	6.97	262.57	1454.72	1560.73	1532.09
23000	0.00066	15.54167	18.38778	33.930	7.28	274.37	1520.10	1630.87	1600.94
23500	0.00068	16.22474	19.19594	35.421	7.60	286.43	1586.91	1702.55	1671.30
24000	0.00071	16.92250	20.02148	36.945	7.93	298.75	1655.15	1775.77	1743.17
24500	0.00074	17.63495	20.86440	38.500	8.26	311.33	1724.84	1850.53	1816.56
25000	0.00077	18.36209	21.72470	40.088	8.60	324.16	1795.96	1926.83	1891.47
25500	0.00081	19.10392	22.60237	41.707	8.95	337.26	1868.51	2004.67	1967.88
26000	0.00084	19.86044	23.49743	43.359	9.30	350.61	1942.51	2084.06	2045.81
26500	0.00087	20.63164	24.40987	45.042	9.67	364.23	2017.94	2164.99	2125.25
27000	0.00090	21.41754	25.33968	46.758	10.03	378.10	2094.80	2247.45	2206.21
27500	0.00094	22.21813	26.28688	48.506	10.41	392.24	2173.11	2331.46	2288.67
28000	0.00097	23.03341	27.25146	50.286	10.79	406.63	2252.85	2417.02	2372.65
28500	0.00101	23.86337	28.23341	52.098	11.18	421.28	2334.02	2504.11	2458.15
29000	0.00104	24.70803	29.23275	53.942	11.57	436.19	2416.64	2592.74	2545.16
29500	0.00108	25.56737	30.24947	55.818	11.98	451.36	2500.69	2682.92	2633.68
30000	**0.00112**	**26.44141**	**31.28356**	**57.726**	**12.39**	**466.79**	**2586.18**	**2774.64**	**2723.71**
30500	0.00115	27.33014	32.33504	59.666	12.80	482.48	2673.10	2867.89	2815.26
31000	0.00119	28.23355	33.40389	61.639	13.23	498.43	2761.46	2962.69	2908.32
31500	0.00123	29.15165	34.49013	63.643	13.66	514.64	2851.26	3059.04	3002.89
32000	0.00127	30.08445	35.59374	65.679	14.09	531.11	2942.49	3156.92	3098.98
32500	0.00131	31.03193	36.71474	67.748	14.54	547.84	3035.17	3256.34	3196.58
33000	0.00135	31.99411	37.85311	69.849	14.99	564.82	3129.27	3357.31	3295.69

Kinetic Energy Storage: E = K*I*ω^2
where (ω^2) = (w*2*Pi/60)^2)

Shaft Inertia (thick cylinder): I_{shaft} = 0.5*m*(R1^2 +R2^2)

Hub-disk Inertia (thick cylinder): I_{hub} = 0.5*m*(R2^2 +R3^2)

Conical disk interia: $I_{overwrap}$ = 3/10*m*R4^2

Solid Cylinder Radial Stress: $\sigma_{r\_max} = \sigma_{t\_max} = \rho\omega^2(3-2\upsilon)/8(1-\upsilon))R_4^2$

Hollow Cylinder Radial Stress: $\sigma_{r\_max} = \rho\omega^2(3-2\upsilon)/8(1-\upsilon)((R_4^2 - R_3^2)$...

Hollow Cylinder Hoop Stress: $\sigma_{t\_max} = \rho\omega^2/4(1-\upsilon)[(1-2\upsilon)R_3^2 + (3-2\upsilon)R_4^2]$

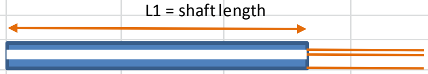
Target Design is >=15% over KWh requirement at break point of 40% and 25% safety factor

Assume K=0.8 for the advanced flywheel while using the Cylinder stress equations since complex toroidal stress analysis equations are unavailable. Overwrap modeled as a conical disk with an added thickness to the overwrap cylinder to take axial loads along composite fiber strength (K=0.9)

Solid cylinder rotor design with CC-CNT Composite

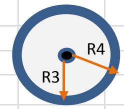
Pi =	3.141592654
~1.4 safety factor	
~1.25 safety factor	

L1 = shaft length



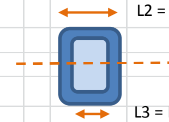
R1 = inner shaft radius
R2 = outer shaft radius

R3 = Cycinder Inner Radius



R4 = Cycinder Outer Radius

L2 = Cyclinder length



L3 = Hub length

Shaft Specifications

0.25	Poisson's Ratio
1350	Shaft material density
4560	Shaft material (MPa)
CNT	Shaft Material Description

Hub Specifications

0.25	Poisson's Ratio
1350	Hub & disk material density kg/m^3
4560	Hub & disk MPa tensile strength
CNT	Hub & Disk Material Description

Rim Specifications

0.25	Poisson's Ratio
1350	Rim material density (kg/m^3)
4560	Rim MPa tensile strength (MPa)
CNT	Hub & Disk Material Description

Design Specifications

0.4	Rim K factor
0	Hub disk K factor
0.5	Shaft K factor
0.98	Storage effeciency

Flywheel Specs

0.5649	Shaft length, l1 (m)
0.03	Shaft radius, R2 (m)
0.02	Shaft inner radius, R1 (m)
1.20	Shaft mass (kg)
0.001	Shaft Inertia (kg-m^2)
Rev step	500

0.0000	Hub-Disk Length, L3 (m)
0.0000	Hub-Disk volume (m^3)
0.00	Hub-Disk mass (kg)
1350.00	Hub-disk effective Density (kg/m^3)
0.000	Hub-Disk Inertia (kg-m^2)

312.00	Rim cylinder mass (kg)
0.0668	Cylinder inner diameter (% of radius)
0.2311	Rim structure volume (m^3)
31.73096216	Rim Cylinder Inertia (kg-m^2)
0.03006	Cylinder inner diameter, R3 (m)

50	Energy storage target kWh
0.4500	Rotor Rim Outer Radius, R4 (m)
0.3649	Rotor Rim Cylinder Height, L2 (m)
313.20	Total Rotor + shaft Mass (kg)
159.64	Watts-hr/kg estimate
0.215381	kWh/liter estimate

Rotor rev/min	Stored Energy (shaft) (kWh)	Stored Energy (Hub) (kWh)	Stored Energy (Cylinder) (kWh)	Total Energy Stored (kWh)	Shaft Hoop or radial Stress est. (Mpa)	Cylinder Radial Stress (MPa)	Cylinder Hoop Stress (MPa)	Hub-Disk Radial Stress (Mpa)	Hub-Disk Hoop Stress (Mpa)
30000	0.00105	0.00000	34.10096	34.102	5.00	1119.19	2250.43	0.02	12.03
30500	0.00108	0.00000	35.24713	35.248	5.16	1156.81	2326.07	0.02	12.44
31000	0.00112	0.00000	36.41224	36.413	5.34	1195.05	2402.95	0.02	12.85
31500	0.00115	0.00000	37.59630	37.597	5.51	1233.91	2481.09	0.02	13.26
32000	0.00119	0.00000	38.79931	38.800	5.68	1273.39	2560.48	0.02	13.69
32500	0.00123	0.00000	40.02126	40.022	5.86	1313.50	2641.12	0.02	14.12
33000	0.00127	0.00000	41.26216	41.263	6.05	1354.22	2723.02	0.02	14.56
33500	0.00130	0.00000	42.52200	42.523	6.23	1395.57	2806.16	0.02	15.00
34000	0.00134	0.00000	43.80078	43.802	6.42	1437.54	2890.55	0.03	15.45
34500	0.00138	0.00000	45.09851	45.100	6.61	1480.13	2976.19	0.03	15.91
35000	0.00142	0.00000	46.41519	46.417	6.80	1523.35	3063.08	0.03	16.38
35500	0.00146	0.00000	47.75081	47.752	7.00	1567.18	3151.22	0.03	16.85
36000	0.00151	0.00000	49.10538	49.107	7.19	1611.64	3240.61	0.03	17.33
36500	0.00155	0.00000	50.47889	50.480	7.40	1656.72	3331.26	0.03	17.81
37000	0.00159	0.00000	51.87134	51.873	7.60	1702.42	3423.15	0.03	18.30
37500	0.00163	0.00000	53.28274	53.284	7.81	1748.74	3516.29	0.03	18.80
38000	0.00168	0.00000	54.71309	54.715	8.02	1795.68	3610.68	0.03	19.30
38500	0.00172	0.00000	56.16238	56.164	8.23	1843.25	3706.33	0.03	19.82
39000	**0.00177**	**0.00000**	**57.63062**	**57.632**	**8.44**	**1891.44**	**3803.22**	**0.03**	**20.33**
39500	0.00181	0.00000	59.11780	59.120	8.66	1940.25	3901.36	0.03	20.86
40000	0.00186	0.00000	60.62392	60.626	8.88	1989.68	4000.76	0.04	21.39
40500	0.00191	0.00000	62.14899	62.151	9.11	2039.73	4101.40	0.04	21.93
41000	0.00195	0.00000	63.69301	63.695	9.33	2090.40	4203.30	0.04	22.47

Kinetic Energy Storage: E = K*I*ω^2
where (ω^2) = (w*2*Pi/60)^2)

Shaft Inertia (thick cylinder): I_{shaft} = 0.5*m*(R1^2 +R2^2)

Hub-disk Inertia (thick cylinder): I_{hub} = 0.5*m*(R2^2 +R3^2)

Solid Cylinder Radial Stress: $\sigma_{r\_max} = \sigma_{t\_max} = \rho\omega^2(3-2\upsilon)/8(1-\upsilon))R_4^2$

Hollow Cylinder Radial Stress: $\sigma_{r\_max} = (\rho\omega^2(3-2\upsilon)/8(1-\upsilon))*(R_4^2 - R_3^2)$

Hollow Cylinder Hoop Stress: $\sigma_{t\_max} = \rho\omega^2/4(1-\upsilon)\,[(1-2\upsilon)R_3^2 + (3-2\upsilon)R_4^2]$

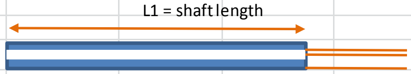
Target Design is >=15% over KWh requirement at break point of 40% and 25% safety factor

Assume K=0.4 for the solid cylinder flywheel due to radial composit wrap not optimal for radial stress.

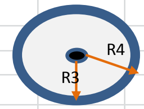
Hollow cylinder + hub rotor design with CC-CNT Composite

Pi =	3.141592654
~1.4 safety factor	
~1.25 safety factor	

L1 = shaft length

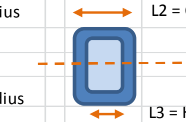


R1 = inner shaft radius
R2 = outer shaft radius



R3 = Cyclinder Inner Radius
R4 = Cyclinder Outer Radius

L2 = Cyclinder length



L3 = Hub length

Shaft Specifications

0.25	Poisson's Ratio
1350	Shaft material density
4560	Shaft material (MPa)
CNT	Shaft Material Description

Hub Specifications

0.25	Poisson's Ratio
1350	Hub & disk material density kg/m^3
4560	Hub & disk MPa tensile strength
CNT	Hub & Disk Material Description

Rim Specifications

0.25	Poisson's Ratio
1350	Rim material density (kg/m^3)
4560	Rim MPa tensile strength (MPa)
CNT	Hub & Disk Material Description

Design Specifications

0.5	Rim K factor
0.5	Hub disk K factor
0.5	Shaft K factor
0.98	Storage effeciency

Flywheel Specs

0.6232	Shaft length, l1 (m)
0.03	Shaft radius, R2 (m)
0.02	Shaft inner radius, R1 (m)
1.32	Shaft mass (kg)
0.001	Shaft Inertia (kg-m^2)
Rev step	500

0.1100	Hub-Disk Length, L3 (m)
0.0391	Hub-Disk volume (m^3)
52.72	Hub-Disk mass (kg)
5421.48	Hub-disk effective Density (kg/m^3)
3.026	Hub-Disk Inertia (kg-m^2)

159.00	Rim cylinder mass (kg)
0.7500	Cylinder inner diameter (% of radius)
0.1178	Rim structure volume (m^3)
25.15429688	Rim Cylinder Inertia (kg-m^2)
0.3375	Cylinder inner diameter, R3 (m)

50	Energy storage target kWh
0.4500	Rotor Rim Outer Radius, R4 (m)
0.4232	Rotor Rim Cylinder length L2 (m)
213.04	Total Rotor + shaft Mass (kg)
234.70	Watts-hr/kg estimate
0.185731	kWh/liter estimate

Rotor rev/min	Stored Energy (shaft) (kWh)	Stored Energy (Hub) (kWh)	Stored Energy (Cylinder) (kWh)	Total Energy Stored (kWh)	Shaft Hoop or radial Stress (Mpa)	Cylinder Radial Stress (MPa)	Cylinder Hoop Stress (MPa)	Hub-Disk Radial Stress (Mpa)	Hub-Disk Hoop Stress (Mpa)
30000	0.00115	4.06544	33.79135	37.858	20.07	491.84	2501.37	2519.47	262.94
30500	0.00119	4.20208	34.92711	39.130	20.74	508.37	2585.44	2604.15	271.78
31000	0.00123	4.34099	36.08165	40.424	21.43	525.18	2670.90	2690.23	280.76
31500	0.00127	4.48215	37.25496	41.738	22.12	542.26	2757.76	2777.71	289.89
32000	0.00131	4.62557	38.44704	43.074	22.83	559.61	2846.00	2866.59	299.17
32500	0.00135	4.77125	39.65790	44.431	23.55	577.23	2935.63	2956.87	308.59
33000	0.00140	4.91918	40.88753	45.808	24.28	595.13	3026.65	3048.56	318.16
33500	0.00144	5.06938	42.13593	47.207	25.02	613.30	3119.06	3141.64	327.87
34000	0.00148	5.22183	43.40311	48.626	25.77	631.74	3212.87	3236.12	337.73
34500	0.00153	5.37655	44.68906	50.067	26.54	650.46	3308.06	3332.00	347.74
35000	0.00157	5.53352	45.99378	51.529	27.31	669.45	3404.64	3429.27	357.89
35500	0.00162	5.69275	47.31727	53.012	28.10	688.72	3502.61	3527.95	368.19
36000	0.00166	5.85423	48.65954	54.515	28.89	708.25	3601.97	3628.03	378.63
36500	0.00171	6.01798	50.02058	56.040	29.70	728.06	3702.72	3729.51	389.22
37000	**0.00176**	**6.18399**	**51.40039**	**57.586**	**30.52**	**748.15**	**3804.86**	**3832.39**	**399.96**
37500	0.00180	6.35225	52.79898	59.153	31.35	768.50	3908.39	3936.67	410.84
38000	0.00185	6.52277	54.21634	60.741	32.19	789.13	4013.30	4042.34	421.87
38500	0.00190	6.69556	55.65247	62.350	33.05	810.04	4119.61	4149.42	433.05
39000	0.00195	6.87060	57.10738	63.980	33.91	831.21	4227.31	4257.90	444.37
39500	0.00200	7.04789	58.58105	65.631	34.79	852.66	4336.40	4367.78	455.84
40000	0.00205	7.22745	60.07351	67.303	35.67	874.39	4446.87	4479.05	467.45
40500	0.00210	7.40927	61.58473	68.996	36.57	896.38	4558.74	4591.73	479.21
41000	0.00216	7.59334	63.11473	70.710	37.48	918.65	4672.00	4705.80	491.11

Kinetic Energy Storage: E = K*I*ω^2
where (ω^2) = (w*2*Pi/60)^2
Shaft Inertia (thick cylinder): I_{shaft} = 0.5*m*(R1^2 +R2^2)
Hub-disk Inertia (thick cylinder): I_{hub} = 0.5*m*(R2^2 +R3^2)

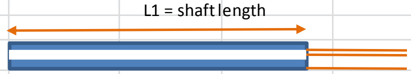
Solid Cylinder Radial Stress: $\sigma_{r\_max} = \sigma_{t\_max} = \rho\omega^2(3-2\upsilon)/8(1-\upsilon))R_4^2$
Hollow Cylinder Radial Stress: $\sigma_{r\_max} = \rho\omega^2(3-2\upsilon)/8(1-\upsilon)((R_4^2 - R_3^2))$...
Hollow Cylinder Hoop Stress: $\sigma_{t\_max} = \rho\omega^2/4(1-\upsilon)[(1-2\upsilon)R_3^2 + (3-2\upsilon)R_4^2]$

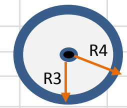
Target Design is >=15% over KWh requirement at break point of 40% and 25% safety factor

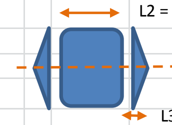
Hub disk composits oriented for radial strength
Cylinder oriented for hoop strength

Reinforced 3-D disk rotor design with CC-CNT Composite

Pi =	3.141592654
~1.4 safety factor	
~1.25 safety factor	







Shaft Specifications

0.25	Poisson's Ratio
1350	Shaft material density
4560	Shaft material (MPa)
CNT	Shaft Material Description

Overwrap Specifications

0.25	Poisson's Ratio
1350	Overwrap material density kg/m^3
4560	Overwrap MPa tensile strength
CNT	Overwrap Material Description

Rim Specifications

0.25	Poisson's Ratio
1350	Rim material density (kg/m^3)
4560	Rim MPa tensile strength (MPa)
CNT	Hub & Disk Material Description

Design Specifications

0.8	Rim K factor
0.9	Overwrap disk K factor
0.5	Shaft K factor
0.98	Storage effeciency

Flywheel Specs

0.3849	Shaft length, l1 (m)
0.03	Shaft radius, R2 (m)
0.02	Shaft inner radius, R1 (m)
0.82	Shaft mass (kg)
0.001	Shaft Inertia (kg-m^2)
Rev step:	500

90.00	Overwrap Disk mass, each side (kg)
0.0197	Overwrap volume (m^3)
0.05	Overwrap height, L3 (m)
5.468	Overwrap Inertia, each side (kg-m^2)
0.009307307	Overwrap top thickness (m)
3154.00	Effective Density (kg/m^3)

34.50	Rim cylinder mass (kg)
0.7500	Cylinder inner diameter (% of radius)
0.0256	Rim structure volume (m^3)
5.458	Rim Cylinder Inertia (kg-m^2)
0.3375	Cylinder inner diameter, R3 (m)
0.4407	Cylinder outer diameter, R4 (m)

50	Energy storage target kWh
0.4500	Rotor Rim Outer Radius, R5 (m)
0.0918	Rotor Rim Cylinder Height, L2 (m)
215.32	Total Rotor + shaft Mass (kg)
232.22	Watts-hr/kg estimate
0.510796	kWh/liter estimate

Rotor rev/min	Stored Energy (shaft) kWh	Stored Energy (Overwrap) (kWh)	Stored Energy (Cylinder) (kWh)	Total Energy Stored (kWh)	Shaft Hoop or radial Stress (Mpa)	Cylinder Radial Stress (MPa)	Cylinder Hoop Stress (MPa)	Overwrap Radial Stress (Mpa)	Overwrap Hoop Stress (Mpa)
30000	0.00071	26.44141	11.73134	38.173	11.67	445.82	2409.32	2614.81	2501.37
30500	0.00074	27.33014	12.12564	39.457	12.07	460.80	2490.30	2702.70	2585.44
31000	0.00076	28.23355	12.52646	40.761	12.46	476.04	2572.62	2792.04	2670.90
31500	0.00079	29.15165	12.93380	42.086	12.87	491.52	2656.28	2882.83	2757.76
32000	0.00081	30.08445	13.34765	43.433	13.28	507.24	2741.27	2975.08	2846.00
32500	0.00084	31.03193	13.76803	44.801	13.70	523.22	2827.61	3068.77	2935.63
33000	0.00086	31.99411	14.19492	46.190	14.12	539.44	2915.28	3163.92	3026.65
33500	0.00089	32.97097	14.62832	47.600	14.56	555.91	3004.29	3260.53	3119.06
34000	0.00092	33.96252	15.06825	49.032	14.99	572.63	3094.64	3358.58	3212.87
34500	0.00094	34.96877	15.51469	50.484	15.44	589.60	3186.33	3458.09	3308.06
35000	0.00097	35.98970	15.96765	51.958	15.89	606.81	3279.35	3559.05	3404.64
35500	0.00100	37.02532	16.42713	53.453	16.35	624.27	3373.72	3661.47	3502.61
36000	0.00103	38.07563	16.89312	54.970	16.81	641.98	3469.42	3765.33	3601.97
36500	**0.00105**	**39.14063**	**17.36564**	**56.507**	**17.28**	**659.94**	**3566.46**	**3870.65**	**3702.72**
37000	0.00108	40.22032	17.84466	58.066	17.76	678.14	3664.84	3977.42	3804.86
37500	0.00111	41.31470	18.33021	59.646	18.24	696.59	3764.56	4085.65	3908.39
38000	0.00114	42.42377	18.82228	61.247	18.73	715.29	3865.62	4195.32	4013.30
38500	0.00117	43.54753	19.32086	62.870	19.23	734.24	3968.02	4306.45	4119.61
39000	0.00120	44.68598	19.82596	64.513	19.73	753.43	4071.75	4419.03	4227.31
39500	0.00124	45.83912	20.33757	66.178	20.24	772.88	4176.82	4533.07	4336.40
40000	0.00127	47.00695	20.85571	67.864	20.75	792.57	4283.24	4648.56	4446.87
40500	0.00130	48.18947	21.38036	69.571	21.27	812.50	4390.99	4765.50	4558.74
41000	0.00133	49.38668	21.91153	71.300	21.80	832.69	4500.08	4883.89	4672.00

Kinetic Energy Storage: E = K*I*ω^2

where (ω^2) = (w*2*Pi/60)^2)

Shaft Inertia (thick cylinder): I_{shaft} = 0.5*m*(R1^2 +R2^2)

Hub-disk Inertia (thick cylinder): I_{hub} = 0.5*m*(R2^2 +R3^2)

Conical disk interia: $I_{overwrap}$ = 3/10*m*R4^2

Solid Cylinder Radial Stress: $\sigma_{r\_max} = \sigma_{t\_max} = \rho\omega^2(3-2\upsilon)/8(1-\upsilon))R_4^2$

Hollow Cylinder Radial Stress: $\sigma_{r\_max} = \rho\omega^2(3-2\upsilon)/8(1-\upsilon)((R_4^2 - R_3^2)$...

Hollow Cylinder Hoop Stress: $\sigma_{t\_max} = \rho\omega^2/4(1-\upsilon)[(1-2\upsilon)R_3^2 + (3-2\upsilon)R_4^2]$

Target Design is >=15% over KWh requirement at break point of 40% and 25% safety factor

Assume K=0.8 for the advanced flywheel while using the Cylinder stress equations since complex toroidal stress analysis equations are unavailable. Overwrap modeled as a conical disk with an added thickness to the overwrap cylinder to take axial loads along composite fiber strength (K=0.9)

Appendix C: PM motor mass and cost estimate

Calculated based on the cost estimation principles in text “Permanent Magnet Motor Technology” by J.F. Gieras

Motor sizing	Example: 7.5kW motor (kg)	% mass	scaling factor	200kW motor (kg)
Stator Copper mass (mCu)	7.800	20%	18.000	140.400
Mass of rotor & stator stack (mFe)	28.500	72%	18.000	513.000
Mass of NdFeB PMs (mPM)	2.100	5%	18.000	37.800
Mass of composite shaft (mSh)	1.260	3%	18.000	22.680
Total motor Mass	39.660			713.880

Material costs	$ per Kg			
Copper conductor (cCu)	10.550		density of shaft material (kg/m^3)	2200.000
Steel laminations (cFe)	2.750		radius of shaft, r (m)	0.060
NdFeB magnets (cPM)	35.000	includes magnetization		
Shaft composite(cSh)	33.000			
Cost of misc components (CO)	147.000			

Cost Coeffecients	coeffecient	Notes
# of machines built per year (kN)	0.950	1000 units
Frame and bearings (kP)	1.200	bearings integrated in with FES rotor
Coil fabrication (kii)	2.000	93% motor = 2, 95% motor = 2.75, 96% motor = 3.5 and 97.5% motor = 4.5
Rotor windings (ksr)	1.000	no rotor windings in PM motor
Utilization of electrotechnical steel (ku)	1.300	93% motor = 1.3, 95% motor = 1.5, 96% motor = 1.7 and 97.5% motor = 2
Insulation stacking factor (ki)	0.960	
Stamping, stacking and misc. ops (kss)	1.400	
PM shape complexity (kshPM)	1.150	
PM magnetization (kmagn)	1.000	
Volume of shaft bar to volume of shaft (kush)	1.000	Included with the rotor shaft
Cost of manufacturing shaft (km)	4.000	(3.15 for steel, 4.0 for composites)

Component costs	Cost (93% motor)	Cost (95% motor)	Cost (96% motor)	Cost (97.5% motor)
Laminated stack w/ frame, Ccl = (kp)(ku)(ki)(kss)(mFe)(cFe)	2957.835	3412.886	3867.938	4550.515
Copper winding, Cw = (kii)(ksr)(mCu)(cCu)	2962.440	4073.355	5184.270	6665.490
Cost of PMs, CPM = (kshPM)(kmagn)(mPM)(cPM)	1521.450	1521.450	1521.450	1521.450
Cost of Shaft, Csh = (kush)(km)(mSh)(cSh)	2993.760	2993.760	2993.760	2993.760
Total cost of motor, C = (kN)(Ccl + Cw + CPM + Csh + C0)	10060.711	11548.379	13036.047	15091.654
Shaft length (SL) = shaft mass/material density/(pi*r^2)/effeciency	0.980	0.960	0.950	0.935

Appendix D: Detailed FES technology database

		Database entry	TRL ranking	Mass (kg)	Length (m)	Shaft Radius (m)	Rotor Radius (m)	Rotor Efficiency (%)	Rotor design speed (rpm)	Power use (watts)	Complexity factor	Material Cost ($/kg)	Build Cost ($)	Unit Cost ($)	Dev. Cost ($)	Dev. schedule (months)	Ops cost ($/yr.)	Maint. cost ($/yr.)	Recycling /Disposal cost ($)
Rotor materials and design	1	Steel (3-D)	5	4914	2.44	0.03	0.45	98%	5600	0	4	$1.80	$9,229	$17,170	$1,738,280	16.38	$600	$300	-$2,211
	2	E-glass (S)	7	1597	1.39	0.03	0.45	98%	17250	0	1	$2.70	$2,399	$6,376	$595,970	4.96	$600	$75	-$647
	3	E-glass (C&H)	5	1073	1.55	0.03	0.45	98%	16500	0	2.5	$2.70	$5,268	$7,757	$1,421,460	13.21	$600	$188	-$435
	4	E-glass (3-D)	4	668	1.32	0.03	0.45	98%	16500	0	4	$2.70	$8,167	$9,472	$2,066,700	19.67	$600	$300	-$271
	5	S-glass (S)	7	863	0.893	0.03	0.45	98%	23500	0	1	$16.00	$2,216	$15,223	$588,630	4.89	$600	$75	-$2,071
	6	S-glass (C&H)	5	602	1.03	0.03	0.45	98%	22000	0	2.5	$16.00	$5,151	$14,043	$1,412,040	13.12	$600	$188	-$1,445
	7	S-glass (3-D)	4	426	0.819	0.03	0.45	98%	22000	0	4	$16.00	$8,107	$14,176	$2,060,650	19.61	$600	$300	-$1,022
	8	AS4C (S)	7	703	0.953	0.03	0.45	98%	26000	0	1	$23.00	$2,176	$17,428	$587,030	4.87	$600	$75	-$2,425
	9	AS4C (C&H)	5	484	1.09	0.03	0.45	98%	24500	0	2.5	$23.00	$5,121	$15,440	$1,409,680	13.10	$600	$188	-$1,670
	10	AS4C (3-D)	4	358	0.823	0.03	0.45	98%	24500	0	4	$23.00	$8,090	$15,507	$2,058,950	19.59	$600	$300	-$1,235
	11	IM10 (S)	7	465	0.697	0.03	0.45	98%	32000	0	1	$64.00	$2,116	$30,282	$584,650	4.85	$600	$75	-$4,464
	12	IM10 (C&H)	5	323	0.794	0.03	0.45	98%	30000	0	2.5	$64.00	$5,081	$24,465	$1,406,460	13.06	$600	$188	-$3,101
	13	IM10 (3-D)	4	273	0.553	0.03	0.45	98%	30000	0	4	$64.00	$8,068	$24,263	$2,056,825	19.57	$600	$300	-$2,621
	14	CNT (S)	5	313	0.562	0.03	0.45	98%	39000	0	1.5	$200.00	$3,078	$62,394	$1,246,260	11.46	$600	$113	-$9,390
	15	CNT (C&H)	4	213	0.623	0.03	0.45	98%	37000	0	3	$200.00	$6,053	$46,221	$1,855,325	17.55	$600	$225	-$6,390
	16	CNT (3-D)	3	215	0.383	0.03	0.45	98%	36500	0	4.5	$200.00	$9,054	$49,451	$2,586,450	24.86	$600	$338	-$6,450

S = Solid Rotor, C&H = Hollow Cylinder & Hub, & 3-D = Advanced 3-D rotor

Assumptions

Build to cost based on ($1000 base)*(complexity factor)+(rotor mass*0.25) to allow for special handling of massive rotors

Unit costs based on 2500 units purchased @ 95% cost curve *(Materials Cost*Material Mass + build cost)

Development cost estimate based on 20*(build cost)*(9-TRL) + $250K base*(9-TRL)

Development schedule based on $100K/month + $100K start-up with a 1 month minimum

Operational cost based on one $50/man-hr. per month for remote monitoring of speed, vibration & temperature sensors

Maintenance cost based on reoccurring 10 yr. rotor inspection (5 man-hours @ $150/man-hr. * rotor complexity factor)

Disposal costs: metal recycling/scrap = 0.25 return; composites recycling/scrap = 0.15 return

Current CNT production requires base composite laminate to be impregnated with CNT whiskers, adds complexity

		Database entry	TRL ranking	Total mass (kg)	Efficiency (%)	Length (m)	Power use (watts)	Complexity factor	Unit Cost ($)	Development Cost ($)	Development schedule (months)	Operations cost ($/yr.)	Maintenance cost ($/yr.)	Recycling /Disposal cost ($)
Motor/Generator + cooling	1	93% + passive	7	1,093	93.0%	0.930	150	1	$15,063	$902,538	8.03	$1,092	$150	-$4,519
	2	93% + active	7	899	93.0%	0.930	235	1.1	$13,293	$831,706	7.32	$1,291	$165	-$3,988
	3	93% + active + TEG	6	900	93.0%	0.930	0	1.2	$13,388	$1,253,259	11.53	$1,080	$180	-$4,016
	4	95% + passive	6	984	95.0%	0.960	150	1.2	$15,442	$1,376,493	12.76	$1,272	$180	-$4,632
	5	95% + active	6	823	95.0%	0.960	235	1.3	$13,993	$1,289,568	11.90	$1,471	$195	-$4,198
	6	95% + active + TEG	5	824	95.0%	0.960	0	1.4	$14,088	$1,727,024	16.27	$1,260	$210	-$4,226
	7	96% + passive	5	932	96.0%	0.950	150	1.4	$16,360	$1,908,816	18.09	$1,452	$210	-$4,908
	8	96% + active	5	805	96.0%	0.950	235	1.5	$15,230	$1,818,376	17.18	$1,651	$225	-$4,569
	9	96% + active + TEG	4	806	96.0%	0.950	0	1.6	$15,325	$2,282,470	21.82	$1,440	$240	-$4,597
	10	97.5% + passive	4	872	97.5%	0.935	150	1.5	$17,743	$2,524,340	24.24	$1,542	$225	-$5,323
	11	97.5% + active	4	779	97.5%	0.935	235	1.6	$16,936	$2,443,590	23.44	$1,741	$240	-$5,081
	12	97.5% + active + TEG	3	780	97.5%	0.935	0	1.7	$17,031	$2,943,708	28.44	$1,530	$255	-$5,109

Assumptions cost do not include G&A or Profit

Total mass calculation = motor mass + cooling mass

Build to cost based on component models

Unit costs based on 100 units purchased @ 95% cost curve *(build cost + heat sink cost) + $2K integration cost

Development cost estimate based on 20*(build cost)*(9-TRL) + $150K base*(9-TRL)

Development schedule based on $100K/month + $100K start-up with a 1 month minimum

Operational cost based on 1.5 $50/man-hr. per month x (complexity factor) for remote monitoring of speed, vibration & temperature sensors + cooling system inspection + power usage based on $0.15/KWh

Maintenance cost based on reoccurring 5 yr. motor/generator inspection (5 man-hours @ $150/man-hr. * rotor complexity factor)

Disposal costs: magnet & metal recycling/scrap = 0.30 return

Control & monitoring electronics add $1000 cost, 10 kg, and 150 w power consumption

PM frequency rectifier to 60hz at 480v included in the control electronics

Motor rotor mass (kg) = 22.7+37.8+(0.25*51 188.75 (composite rotor shaft, PM magnets and rotor casing masses supported by the shaft bearings)

		Database entry	TRL ranking	Density (kg/m^3)	Radial load capacity (kg/cm^2)	Axial load capacity (kg/cm^2)	Power use (watts/cm)	Complexity factor	Unit Cost + install ($/kg)	Development cost ($/kg)	Operations cost ($/yr./cm)	Maintenance cost ($/yr.)	Recycling /Disposal cost ($/kg)
Bearings	1	NeFeB PM N42 grade	7	8400	4.2	5.95	0	1.25	$196	$784	$0	$0	-0.30
	2	Sa-Co PM 24 grade	7	7400	2.4	3.4	0	1.35	$212	$846	$0	$0	-0.30
	3	Active Magnets (COTS)	8	5500	5.1	3.24	9.26	4	$627	$1,254	$12	$75	-0.20

Assumptions

Shaft outer radius = 3cm, rotor magnet outer radius limited to 4.5cm to stay within material strengths. Magnet stator outer radius at 6cm.

Frictional losses are considered negligible

Length and mass of magnetic bearings are based on a normalized 1 cm "stack" and placed in rings along the shaft until they can handle the FES rotor and motor/generator rotor mass +25% safety factor

Unit cost based on complexity factor*1.5*(material mass) to account for install labor and testing

Development cost based design and integrating the bearing system into the design @ (2)*(unit cost)*(9-TRL)

Development schedule based on $50K/month + $50K start-up with a 1 month minimum

PM sets have two radial bearing sets for the FES rotor and two radial bearing sets for the motor/generator rotor

PM sets have one passive axial bearing (20% radial load), and one small active axial thrust bearing (10% radial load)

Active bearing design requires two radial active bearing sets to support the rotor and two radial bearing sets to support the motor/generator rotor + one large active axial thrust bearing (30% radial load)

Active bearing operation cost based on $0.15/KWh electrical costs of unit 24/365 operation

COTS active bearing are Synchony novaglide http://www.synchrony.com/products/magnetic-bearings/novaglide-magnetic-bearings.aspx

COTS Novaglide NR 35-20 radial bearing can support up to 849 lbs (394 kg) @ 34,000 rpm, ~10kg and are 3.4" (0.0864 m) long and use ~50w when loaded ($1200 each)

COTS Novaglide NT 45-10 axial bearing can support up to 525 lbs (244 kg) @ 34,000 rpm, ~6kg and are 3.3" (0.0838 m) long and use ~35w when loaded ($1100 each)

COTS active bearings require one planned replacement at 110,000 hrs. MTBF (12 years) = 10hrs, $150/man-hr. over 20 years

		Database entry	TRL ranking	Air density (kg/m^3)	Cm constant	Material density (kg/m^3)	Material cost ($/kg)	Power use (watts)	Enclosure thickness (m)	Complexity factor	Vacuum pump mass (kg)	Vacuum pump cost ($)	Operations cost ($/yr.)	Maintenance cost ($/yr.)	Recycling /Disposal cost ($/kg)
Vacuum	1	Pumped enclosure, medium vacuum (25 Torr) with e-glass composite enclosure	7	0.04	0.027	2,120	2.70	120	0.01	1	9.5	$2,685	$16	$150	-0.15
	2	Sealed enclosure, high vacuum (0.1 Torr) with e-glass composite enclosure	7	0.016	0.0007	2,120	2.70	0	0.012	2	0	$0	$0	$0	-0.15

Vacuum enclosure mass based on length of FES components (Rotor, bearings, & motor)

Complexity factor deals with seals

Frictional losses based on vacuum level and rotor radius and equation Ma= ρ_g ω^2 r_0^5 Cm and calculated for design rotational speed of rotor

Unit cost = material cost*(2+complexity factor) + vacuum pump

Vacuum pump expected to operate 10% of time to maintain vacuum level, with power cost at $0.15/KWh

Developmental cost = 5*unit cost*(9-TRL)

Development schedule based on $50K/month + $50K start-up with a 1 month minimum

Maintenance cost = 0.25 $50/man-hour per month to clean/check vacuum pump

Vacuum pump based on Agilent Technologies (Varian) IDP-3 pump, 0.12Kw, $2826, 9.5kg http://www.lesker.com/newweb/Vacuum_Pumps/scrollpump_varian.cfm

Disposal costs: composites recycling/scrap = 0.15 return

Support structure made from E-glass composite and adds 0.15m in length to the overall system 0.15

Support structure made from E-glass composite and is estimated at 10% rotor+bearing+motor+ vacuum enclosure mass

Appendix E: Detailed STMI "Best Value" VE analysis

All successful baseline FES design runs + last page of unsuccessful designs which did not meet customer requirements

	A	B	C	D	E	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO
1									Sensitivity analysis variables								
2									0%	0%	0%		0%	0%	# of successful designs		407
3	All cases analysis (baseline)					Constraints										MinWorth	Best Value
4						1600.0	2.7	85%	10000000	10000000	10000000	1000000	10000000	1000000		$1,939,384	0.9920
5		Technology Number				Mass	Length	Effeciency	System Unit	Development	20 yr Ops	20 yr Ops	20 yr Maint.	Recycling/	Successful		
6	Run #	Rotor	Motor/Gen	Bearings	Vac.	(kg)	(m)	(%)	cost ($)	cost ($)	cost ($)	cost+eff.	cost ($)	disposal cost ($)	design? (Y/N)	Worth ($)	Best Value
7	1	11	5	1	2	1583.5	1.966	87.2%	$57,369	$1,882,015	$41,424	$18,680	$5,400	-$8,357	Y	$1,939,384	0.9920
8	2	11	5	3	2	1558.6	1.952	86.7%	$68,870	$1,881,753	$48,422	$29,924	$6,900	-$8,348	Y	$1,950,622	0.9799
9	3	11	5	1	1	1566.6	1.966	86.8%	$59,279	$1,905,000	$41,744	$22,313	$8,400	-$8,382	Y	$1,964,279	0.9762
10	4	11	5	3	1	1541.8	1.952	86.4%	$70,788	$1,904,759	$48,743	$33,557	$9,900	-$8,371	Y	$1,975,547	0.9646
11	5	11	6	1	2	1584.6	1.966	88.0%	$57,465	$2,299,479	$37,200	$6,466	$5,700	-$8,386	Y	$2,356,944	0.8215
12	6	11	6	3	2	1559.7	1.952	87.5%	$68,966	$2,299,217	$44,199	$17,710	$7,200	-$8,376	Y	$2,368,182	0.8133
13	7	11	6	1	1	1567.7	1.966	87.6%	$59,375	$2,322,464	$37,520	$10,100	$8,700	-$8,410	Y	$2,381,838	0.8107
14	8	11	6	3	1	1542.9	1.952	87.2%	$70,883	$2,322,223	$44,519	$21,344	$10,200	-$8,400	Y	$2,393,106	0.8026
15	9	11	8	1	2	1562.8	1.956	89.2%	$58,582	$2,390,631	$45,024	$2,254	$6,000	-$8,729	Y	$2,449,213	0.7920
16	10	11	8	3	2	1537.9	1.942	88.7%	$70,082	$2,390,369	$52,022	$13,498	$7,500	-$8,719	Y	$2,460,451	0.7843
17	11	11	8	1	1	1545.9	1.956	88.8%	$60,498	$2,413,631	$45,344	$5,887	$9,000	-$8,753	Y	$2,474,129	0.7819
18	12	11	8	3	1	1521.1	1.942	88.4%	$72,007	$2,413,390	$52,343	$17,131	$10,500	-$8,742	Y	$2,485,397	0.7744
19	13	11	8	2	1	1583.5	2.164	88.8%	$67,412	$2,441,755	$45,344	$5,887	$9,000	-$8,763	Y	$2,509,167	0.7710
20	14	14	5	1	2	1393.1	1.759	87.2%	$86,530	$2,530,684	$41,424	$18,588	$6,150	-$13,282	Y	$2,617,214	0.7378
21	15	14	5	3	2	1374.0	1.748	86.8%	$95,357	$2,530,483	$46,795	$27,217	$7,650	-$13,275	Y	$2,625,840	0.7326
22	16	14	5	2	2	1423.0	1.919	87.2%	$91,868	$2,552,510	$41,424	$18,588	$6,150	-$13,289	Y	$2,644,378	0.7302
23	17	14	5	1	1	1377.5	1.759	86.8%	$88,518	$2,553,981	$41,744	$22,221	$9,150	-$13,304	Y	$2,642,498	0.7289
24	18	14	5	3	1	1358.5	1.748	86.5%	$97,351	$2,553,796	$47,116	$30,851	$10,650	-$13,295	Y	$2,651,146	0.7238
25	19	14	5	2	1	1406.4	1.919	86.8%	$93,824	$2,575,566	$41,744	$22,221	$9,150	-$13,310	Y	$2,669,390	0.7216
26	20	14	4	1	2	1569.6	1.759	87.5%	$88,152	$2,618,909	$37,445	$11,719	$5,850	-$13,713	Y	$2,707,061	0.7154
27	21	14	4	3	2	1550.5	1.748	87.1%	$96,979	$2,618,708	$42,816	$20,348	$7,350	-$13,706	Y	$2,715,687	0.7105
28	22	14	4	2	2	1599.5	1.919	87.5%	$93,490	$2,640,735	$37,445	$11,719	$5,850	-$13,720	Y	$2,734,225	0.7083
29	23	14	4	1	1	1554.1	1.759	87.1%	$90,096	$2,642,206	$37,765	$15,352	$8,850	-$13,738	Y	$2,732,302	0.7071
30	24	12	5	1	2	1414.4	1.996	87.2%	$48,890	$2,692,667	$41,424	$18,594	$7,650	-$6,994	Y	$2,741,558	0.7025
31	25	14	4	3	1	1535.1	1.748	86.8%	$98,929	$2,642,021	$43,137	$23,982	$10,350	-$13,729	Y	$2,740,950	0.7023
32	26	14	4	2	1	1582.9	1.919	87.1%	$95,403	$2,663,791	$37,765	$15,352	$8,850	-$13,745	Y	$2,759,193	0.7002
33	27	12	5	3	2	1395.0	1.985	86.8%	$57,893	$2,692,462	$46,902	$27,395	$9,150	-$6,987	Y	$2,750,355	0.6976
34	28	12	5	2	2	1444.9	2.159	87.2%	$54,334	$2,714,928	$41,424	$18,594	$7,650	-$7,001	Y	$2,769,262	0.6955
35	29	12	5	1	1	1397.3	1.996	86.8%	$50,837	$2,715,607	$41,744	$22,227	$10,650	-$7,014	Y	$2,766,444	0.6945
36	30	9	5	3	2	1596.6	2.353	86.7%	$54,891	$2,709,963	$48,626	$30,262	$9,150	-$5,555	Y	$2,764,854	0.6930
37	31	12	5	3	1	1377.9	1.985	86.5%	$59,846	$2,715,419	$47,223	$31,029	$12,150	-$7,007	Y	$2,775,265	0.6898
38	32	12	5	2	1	1426.8	2.159	86.8%	$56,249	$2,737,623	$41,744	$22,227	$10,650	-$7,022	Y	$2,793,872	0.6878
39	33	9	5	3	1	1577.1	2.353	86.4%	$56,740	$2,732,365	$48,946	$33,896	$12,150	-$5,579	Y	$2,789,105	0.6854
40	34	12	4	1	2	1591.0	1.996	87.5%	$50,512	$2,780,892	$37,445	$11,725	$7,350	-$7,425	Y	$2,831,405	0.6821
41	35	12	4	3	2	1571.5	1.985	87.1%	$59,515	$2,780,687	$42,923	$20,526	$8,850	-$7,417	Y	$2,840,202	0.6776

Database | Analysis | S

Ready 95%

	A	B	C	D	E	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO
1									Sensitivity analysis variables								
2									0%	0%	0%		0%	0%		# of successful designs	407
3	**All cases analysis (baseline)**					Constraints										MinWorth	Best Value
4						1600.0	2.7	85%	10000000	10000000	10000000	1000000	10000000	1000000		$1,939,384	0.9920
5		Technology Number				Mass	Length	Effeciency	System Unit	Development	20 yr Ops	20 yr Ops	20 yr Maint.	Recycling/	Successful		
6	Run #	Rotor	Motor/Gen	Bearings	Vac.	(kg)	(m)	(%)	cost ($)	cost ($)	cost ($)	cost+eff.	cost ($)	disposal cost ($)	design? (Y/N)	Worth ($)	Best Value
42	36	12	4	1	1	1573.9	1.996	87.1%	$52,416	$2,803,832	$37,765	$15,359	$10,350	-$7,449	Y	$2,856,248	0.6747
43	37	11	9	1	2	1563.9	1.956	90.0%	$58,678	$2,834,733	$40,800	-$9,960	$6,300	-$8,757	Y	$2,893,411	0.6732
44	38	12	4	3	1	1554.5	1.985	86.8%	$61,425	$2,803,644	$43,244	$24,160	$11,850	-$7,441	Y	$2,865,069	0.6702
45	39	11	9	3	2	1539.0	1.942	89.5%	$70,178	$2,834,471	$47,799	$1,284	$7,800	-$8,748	Y	$2,904,650	0.6676
46	40	11	9	1	1	1547.0	1.956	89.6%	$60,594	$2,857,733	$41,120	-$6,326	$9,300	-$8,781	Y	$2,918,327	0.6659
47	41	11	9	3	1	1522.2	1.942	89.2%	$72,103	$2,857,493	$48,119	$4,918	$10,800	-$8,770	Y	$2,929,595	0.6604
48	42	11	9	2	1	1584.6	2.164	89.6%	$67,508	$2,885,857	$41,120	-$6,326	$9,300	-$8,790	Y	$2,953,365	0.6580
49	43	11	11	1	2	1533.6	1.941	92.2%	$60,253	$2,995,572	$46,824	-$25,985	$6,300	-$9,241	Y	$3,055,825	0.6407
50	44	14	6	1	2	1394.2	1.759	88.0%	$86,626	$2,948,148	$37,200	$6,374	$6,450	-$13,311	Y	$3,034,775	0.6392
51	45	11	11	3	2	1508.7	1.927	91.7%	$71,754	$2,995,310	$53,822	-$14,741	$7,800	-$9,231	Y	$3,067,064	0.6357
52	46	14	6	3	2	1375.1	1.748	87.6%	$95,453	$2,947,947	$42,572	$15,004	$7,950	-$13,303	Y	$3,043,400	0.6352
53	47	11	11	1	1	1516.8	1.941	91.8%	$62,179	$3,018,595	$47,144	-$22,352	$9,300	-$9,265	Y	$3,080,774	0.6341
54	48	14	6	2	2	1424.1	1.919	88.0%	$91,964	$2,969,974	$37,200	$6,374	$6,450	-$13,318	Y	$3,061,938	0.6335
55	49	11	11	2	2	1572.6	2.149	92.2%	$67,208	$3,024,010	$46,824	-$25,985	$6,300	-$9,250	Y	$3,091,218	0.6333
56	50	14	6	1	1	1378.6	1.759	87.6%	$88,613	$2,971,445	$37,520	$10,008	$9,450	-$13,331	Y	$3,060,058	0.6325
57	51	11	11	3	1	1492.0	1.927	91.4%	$73,688	$3,018,354	$54,143	-$11,108	$10,800	-$9,255	Y	$3,092,042	0.6292
58	52	14	6	3	1	1359.6	1.748	87.3%	$97,446	$2,971,260	$42,892	$18,637	$10,950	-$13,324	Y	$3,068,706	0.6287
59	53	14	6	2	1	1407.5	1.919	87.6%	$93,920	$2,993,030	$37,520	$10,008	$9,450	-$13,338	Y	$3,086,950	0.6270
60	54	11	11	2	1	1554.4	2.149	91.8%	$69,093	$3,046,719	$47,144	-$22,352	$9,300	-$9,275	Y	$3,115,812	0.6269
61	55	14	8	1	2	1372.3	1.749	89.2%	$87,743	$3,039,301	$45,024	$2,162	$6,750	-$13,654	Y	$3,127,043	0.6211
62	56	14	8	3	2	1353.2	1.738	88.8%	$96,569	$3,039,100	$50,395	$10,791	$8,250	-$13,646	Y	$3,135,669	0.6174
63	57	14	8	2	2	1402.2	1.909	89.2%	$93,080	$3,061,126	$45,024	$2,162	$6,750	-$13,661	Y	$3,154,207	0.6158
64	58	14	8	1	1	1356.8	1.749	88.8%	$89,737	$3,062,612	$45,344	$5,795	$9,750	-$13,673	Y	$3,152,349	0.6149
65	59	11	10	3	1	1594.3	1.927	91.7%	$74,571	$3,099,857	$50,164	-$17,977	$10,500	-$9,497	Y	$3,174,428	0.6142
66	60	12	6	1	2	1415.5	1.996	88.0%	$48,986	$3,110,131	$37,200	$6,380	$7,950	-$7,023	Y	$3,159,118	0.6125
67	61	14	8	3	1	1337.8	1.738	88.5%	$98,570	$3,062,427	$50,716	$14,425	$11,250	-$13,667	Y	$3,160,997	0.6112
68	62	14	8	2	1	1385.7	1.909	88.8%	$95,043	$3,084,197	$45,344	$5,795	$9,750	-$13,682	Y	$3,179,240	0.6097
69	63	12	6	3	2	1396.1	1.985	87.6%	$57,989	$3,109,926	$42,679	$15,182	$9,450	-$7,015	Y	$3,167,915	0.6088
70	64	12	6	2	2	1446.0	2.159	88.0%	$54,430	$3,132,392	$37,200	$6,380	$7,950	-$7,030	Y	$3,186,822	0.6072
71	65	12	6	1	1	1398.4	1.996	87.6%	$50,933	$3,133,071	$37,520	$10,014	$10,950	-$7,043	Y	$3,184,004	0.6065
72	66	9	6	3	2	1597.7	2.353	87.5%	$54,987	$3,127,427	$44,402	$18,048	$9,450	-$5,583	Y	$3,182,415	0.6052
73	67	14	7	1	2	1512.0	1.749	89.5%	$89,010	$3,130,769	$41,045	-$4,707	$6,450	-$13,990	Y	$3,219,780	0.6046
74	68	15	5	1	2	1273.7	1.773	87.2%	$68,479	$3,131,861	$41,424	$18,527	$8,400	-$10,283	Y	$3,200,340	0.6029
75	69	12	6	3	1	1379.0	1.985	87.3%	$59,942	$3,132,883	$42,999	$18,815	$12,450	-$7,036	Y	$3,192,825	0.6028
76	70	12	6	2	1	1427.9	2.159	87.6%	$56,345	$3,155,087	$37,520	$10,014	$10,950	-$7,051	Y	$3,211,432	0.6013

Database | Analysis | S

Ready 95%

	A	B	C	D	E	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO
1									Sensitivity analysis variables								
2									0%	0%	0%		0%	0%	# of successful designs		407
3	**All cases analysis (baseline)**					Constraints										MinWorth	Best Value
4						1600.0	2.7	85%	10000000	10000000	10000000	1000000	10000000	1000000		$1,939,384	0.9920
5		Technology Number				Mass	Length	Effeciency	System Unit	Development	20 yr Ops	20 yr Ops	20 yr Maint.	Recycling/	Successful		
6	Run #	Rotor	Motor/Gen	Bearings	Vac.	(kg)	(m)	(%)	cost ($)	cost ($)	cost ($)	cost+eff.	cost ($)	disposal cost ($)	design? (Y/N)	Worth ($)	Best Value
77	71	14	7	3	2	1492.9	1.738	89.1%	$97,837	$3,130,568	$46,416	$3,922	$7,950	-$13,982	Y	$3,228,405	0.6011
78	72	15	5	3	2	1258.4	1.764	86.9%	$75,546	$3,131,700	$45,725	$25,436	$9,900	-$10,277	Y	$3,207,247	0.6000
79	73	14	7	2	2	1541.9	1.909	89.5%	$94,348	$3,152,595	$41,045	-$4,707	$6,450	-$13,997	Y	$3,246,943	0.5996
80	74	9	6	3	1	1578.2	2.353	87.2%	$56,835	$3,149,829	$44,723	$21,682	$12,450	-$5,609	Y	$3,206,664	0.5995
81	75	15	5	2	2	1297.7	1.901	87.2%	$72,753	$3,149,337	$41,424	$18,527	$8,400	-$10,288	Y	$3,222,090	0.5988
82	76	14	7	1	1	1496.5	1.749	89.1%	$90,970	$3,154,081	$41,365	-$1,074	$9,450	-$14,014	Y	$3,245,051	0.5987
83	77	15	5	1	1	1258.1	1.773	86.8%	$70,494	$3,155,137	$41,744	$22,160	$11,400	-$10,301	Y	$3,225,631	0.5969
84	78	12	8	1	2	1393.7	1.986	89.2%	$50,103	$3,201,284	$45,024	$2,168	$8,250	-$7,366	Y	$3,251,387	0.5959
85	79	14	7	3	1	1477.5	1.738	88.8%	$99,803	$3,153,896	$46,737	$7,556	$10,950	-$14,007	Y	$3,253,699	0.5952
86	80	15	5	3	1	1242.8	1.764	86.6%	$77,566	$3,154,989	$46,045	$29,070	$12,900	-$10,294	Y	$3,232,555	0.5941
87	81	14	7	2	1	1525.4	1.909	89.1%	$96,276	$3,175,666	$41,365	-$1,074	$9,450	-$14,021	Y	$3,271,942	0.5938
88	82	15	5	2	1	1281.2	1.901	86.8%	$74,742	$3,172,420	$41,744	$22,160	$11,400	-$10,307	Y	$3,247,163	0.5930
89	83	12	8	3	2	1374.2	1.975	88.8%	$59,105	$3,201,079	$50,502	$10,969	$9,750	-$7,358	Y	$3,260,184	0.5924
90	84	12	8	2	2	1424.2	2.149	89.2%	$55,547	$3,223,544	$45,024	$2,168	$8,250	-$7,373	Y	$3,279,091	0.5909
91	85	12	8	1	1	1376.6	1.986	88.8%	$52,056	$3,224,239	$45,344	$5,801	$11,250	-$7,385	Y	$3,276,295	0.5902
92	86	9	8	3	2	1575.9	2.343	88.7%	$56,104	$3,218,580	$52,226	$13,836	$9,750	-$5,926	Y	$3,274,684	0.5891
93	87	9	8	1	1	1582.0	2.358	88.8%	$46,116	$3,241,244	$45,344	$5,899	$11,250	-$5,961	Y	$3,287,360	0.5880
94	88	15	4	1	2	1450.3	1.773	87.5%	$70,101	$3,220,087	$37,445	$11,658	$8,100	-$10,713	Y	$3,290,187	0.5878
95	89	12	8	3	1	1357.2	1.975	88.5%	$61,065	$3,224,050	$50,823	$14,603	$12,750	-$7,378	Y	$3,285,115	0.5868
96	90	12	8	2	1	1406.1	2.149	88.8%	$57,468	$3,246,254	$45,344	$5,801	$11,250	-$7,394	Y	$3,303,722	0.5853
97	91	15	4	3	2	1435.0	1.764	87.2%	$77,168	$3,219,925	$41,746	$18,568	$9,600	-$10,707	Y	$3,297,094	0.5851
98	92	15	4	2	2	1474.2	1.901	87.5%	$74,375	$3,237,562	$37,445	$11,658	$8,100	-$10,718	Y	$3,311,937	0.5840
99	93	9	8	3	1	1556.5	2.343	88.4%	$57,959	$3,240,996	$52,546	$17,470	$12,750	-$5,951	Y	$3,298,955	0.5836
100	94	15	4	1	1	1434.6	1.773	87.1%	$72,072	$3,243,362	$37,765	$15,292	$11,100	-$10,735	Y	$3,315,434	0.5822
101	95	12	7	1	2	1533.4	1.986	89.5%	$51,370	$3,292,752	$41,045	-$4,701	$7,950	-$7,702	Y	$3,344,123	0.5807
102	96	15	4	3	1	1419.4	1.764	86.9%	$79,145	$3,243,214	$42,066	$22,201	$12,600	-$10,729	Y	$3,322,359	0.5795
103	97	15	4	2	1	1457.7	1.901	87.1%	$76,321	$3,260,645	$37,765	$15,292	$11,100	-$10,740	Y	$3,336,966	0.5785
104	98	12	7	3	2	1513.9	1.975	89.1%	$60,373	$3,292,547	$46,523	$4,100	$9,450	-$7,694	Y	$3,352,920	0.5774
105	99	12	7	2	2	1563.9	2.149	89.5%	$56,815	$3,315,013	$41,045	-$4,701	$7,950	-$7,709	Y	$3,371,828	0.5759
106	100	12	7	1	1	1516.3	1.986	89.1%	$53,290	$3,315,707	$41,365	-$1,067	$10,950	-$7,725	Y	$3,368,997	0.5753
107	101	12	7	3	1	1496.9	1.975	88.8%	$62,299	$3,315,519	$46,844	$7,734	$12,450	-$7,717	Y	$3,377,818	0.5720
108	102	12	7	2	1	1545.8	2.149	89.1%	$58,702	$3,337,723	$41,365	-$1,067	$10,950	-$7,733	Y	$3,396,424	0.5706
109	103	13	5	1	2	1344.0	1.731	87.2%	$47,634	$3,337,955	$41,424	$18,563	$9,900	-$6,513	Y	$3,385,588	0.5691
110	104	10	5	1	2	1458.2	2.041	87.2%	$40,611	$3,348,128	$41,424	$18,615	$9,900	-$5,129	Y	$3,388,739	0.5684
111	105	7	5	1	2	1540.9	2.070	87.2%	$40,573	$3,355,349	$41,424	$18,656	$9,900	-$4,916	Y	$3,395,921	0.5671

Database | Analysis | S

Ready | 95%

	A	B	C	D	E	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO
1									Sensitivity analysis variables								
2									0%	0%	0%		0%	0%		# of successful designs	407
3	All cases analysis (baseline)					Constraints										MinWorth	Best Value
4						1600.0	2.7	85%	10000000	10000000	10000000	1000000	10000000	1000000		$1,939,384	0.9920
5		Technology Number				Mass	Length	Effeciency	System Unit	Development	20 yr Ops	20 yr Ops	20 yr Maint.	Recycling/	Successful		
6	Run #	Rotor	Motor/Gen	Bearings	Vac.	(kg)	(m)	(%)	cost ($)	cost ($)	cost ($)	cost+eff.	cost ($)	disposal cost ($)	design? (Y/N)	Worth ($)	Best Value
112	106	13	5	3	2	1326.4	1.721	86.9%	$55,757	$3,337,770	$46,367	$26,505	$11,400	-$6,506	Y	$3,393,526	0.5663
113	107	10	5	3	2	1437.4	2.030	86.8%	$50,229	$3,347,909	$47,277	$28,018	$11,400	-$5,121	Y	$3,398,138	0.5650
114	108	13	5	2	2	1371.5	1.878	87.2%	$52,546	$3,358,040	$41,424	$18,563	$9,900	-$6,519	Y	$3,410,586	0.5650
115	109	13	5	1	1	1328.6	1.731	86.8%	$49,638	$3,361,293	$41,744	$22,197	$12,900	-$6,532	Y	$3,410,930	0.5639
116	110	10	5	2	2	1490.8	2.216	87.2%	$46,427	$3,371,911	$41,424	$18,615	$9,900	-$5,136	Y	$3,418,339	0.5635
117	111	7	5	3	2	1517.5	2.056	86.8%	$51,387	$3,355,102	$48,005	$29,229	$11,400	-$4,907	Y	$3,406,489	0.5634
118	112	10	5	1	1	1440.8	2.041	86.8%	$42,540	$3,371,000	$41,744	$22,248	$12,900	-$5,150	Y	$3,413,540	0.5632
119	113	7	5	1	1	1523.3	2.070	86.8%	$42,477	$3,378,178	$41,744	$22,290	$12,900	-$4,939	Y	$3,420,655	0.5620
120	114	7	5	2	2	1577.5	2.265	87.2%	$47,112	$3,382,090	$41,424	$18,656	$9,900	-$4,924	Y	$3,429,202	0.5617
121	115	13	5	3	1	1311.1	1.721	86.5%	$57,766	$3,361,123	$46,687	$30,138	$14,400	-$6,526	Y	$3,418,889	0.5610
122	116	10	5	3	1	1420.1	2.030	86.5%	$52,165	$3,370,798	$47,597	$31,652	$14,400	-$5,143	Y	$3,422,964	0.5599
123	117	13	5	2	1	1355.2	1.878	86.8%	$54,521	$3,381,157	$41,744	$22,197	$12,900	-$6,539	Y	$3,435,678	0.5598
124	118	10	5	2	1	1472.2	2.216	86.8%	$48,322	$3,394,521	$41,744	$22,248	$12,900	-$5,158	Y	$3,442,843	0.5584
125	119	7	5	3	1	1500.0	2.056	86.4%	$53,300	$3,377,951	$48,325	$32,863	$14,400	-$4,930	Y	$3,431,251	0.5583
126	120	7	5	2	1	1558.6	2.265	86.8%	$48,979	$3,404,624	$41,744	$22,290	$12,900	-$4,948	Y	$3,453,603	0.5567
127	121	13	4	1	2	1520.6	1.731	87.5%	$49,256	$3,426,180	$37,445	$11,695	$9,600	-$6,944	Y	$3,475,435	0.5557
128	122	11	12	1	2	1534.7	1.941	93.0%	$60,349	$3,475,698	$42,600	-$38,199	$6,600	-$9,270	Y	$3,536,048	0.5549
129	123	13	4	3	2	1503.0	1.721	87.2%	$57,379	$3,425,995	$42,388	$19,636	$11,100	-$6,937	Y	$3,483,373	0.5530
130	124	13	4	2	2	1548.1	1.878	87.5%	$54,168	$3,446,266	$37,445	$11,695	$9,600	-$6,950	Y	$3,500,433	0.5518
131	125	11	12	3	2	1509.8	1.927	92.5%	$71,850	$3,475,436	$49,599	-$26,955	$10,350	-$9,260	Y	$3,547,286	0.5507
132	126	13	4	1	1	1505.2	1.731	87.1%	$51,216	$3,449,518	$37,765	$15,328	$12,600	-$6,967	Y	$3,500,734	0.5507
133	127	11	12	1	1	1517.9	1.941	92.6%	$62,275	$3,498,721	$42,920	-$34,565	$9,600	-$9,293	Y	$3,560,996	0.5499
134	128	11	12	2	2	1573.7	2.149	93.0%	$67,304	$3,504,136	$42,600	-$38,199	$6,600	-$9,278	Y	$3,571,440	0.5493
135	129	13	4	3	1	1487.7	1.721	86.8%	$59,345	$3,449,348	$42,709	$23,270	$14,100	-$6,959	Y	$3,508,693	0.5480
136	130	10	4	3	1	1596.6	2.030	86.8%	$53,744	$3,459,023	$43,619	$24,783	$14,100	-$5,576	Y	$3,512,767	0.5469
137	131	13	4	2	1	1531.7	1.878	87.1%	$56,100	$3,469,382	$37,765	$15,328	$12,600	-$6,974	Y	$3,525,482	0.5469
138	132	11	12	3	1	1493.1	1.927	92.2%	$73,784	$3,498,480	$49,919	-$23,321	$11,100	-$9,284	Y	$3,572,264	0.5462
139	133	14	9	1	2	1373.4	1.749	90.0%	$87,839	$3,483,403	$40,800	-$10,052	$7,050	-$13,682	Y	$3,571,242	0.5456
140	134	11	12	2	1	1555.5	2.149	92.6%	$69,189	$3,526,845	$42,920	-$34,565	$9,600	-$9,303	Y	$3,596,034	0.5445
141	135	14	9	3	2	1354.3	1.738	89.6%	$96,665	$3,483,202	$46,172	-$1,422	$8,550	-$13,675	Y	$3,579,867	0.5427
142	136	14	9	2	2	1403.3	1.909	90.0%	$93,176	$3,505,229	$40,800	-$10,052	$7,050	-$13,689	Y	$3,598,405	0.5415
143	137	14	9	1	1	1357.9	1.749	89.6%	$89,833	$3,506,714	$41,120	-$6,418	$10,050	-$13,703	Y	$3,596,547	0.5407
144	138	14	9	3	1	1338.9	1.738	89.3%	$98,666	$3,506,529	$46,492	$2,211	$11,550	-$13,695	Y	$3,605,195	0.5379
145	139	14	9	2	1	1386.8	1.909	89.6%	$95,139	$3,528,299	$41,120	-$6,418	$10,050	-$13,711	Y	$3,623,438	0.5367
146	140	15	6	1	2	1274.8	1.773	88.0%	$68,575	$3,549,326	$37,200	$6,313	$8,700	-$10,311	Y	$3,617,900	0.5354

Database | Analysis | S

Ready 95%

	A	B	C	D	E	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO
1									Sensitivity analysis variables								
2									0%	0%	0%		0%	0%		# of successful designs	407
3	All cases analysis (baseline)					Constraints										MinWorth	Best Value
4						1600.0	2.7	85%	10000000	10000000	10000000	1000000	10000000	1000000		$1,939,384	0.9920
5		Technology Number				Mass	Length	Effeciency	System Unit	Development	20 yr Ops	20 yr Ops	20 yr Maint.	Recycling/	Successful		
6	Run #	Rotor	Motor/Gen	Bearings	Vac.	(kg)	(m)	(%)	cost ($)	cost ($)	cost ($)	cost+eff.	cost ($)	disposal cost ($)	design? (Y/N)	Worth ($)	Best Value
147	141	15	6	3	2	1259.5	1.764	87.7%	$75,642	$3,549,164	$41,501	$13,223	$10,200	-$10,305	Y	$3,624,807	0.5331
148	142	15	6	2	2	1298.8	1.901	88.0%	$72,849	$3,566,801	$37,200	$6,313	$8,700	-$10,316	Y	$3,639,650	0.5322
149	143	15	6	1	1	1259.2	1.773	87.6%	$70,589	$3,572,601	$37,520	$9,947	$11,700	-$10,330	Y	$3,643,191	0.5307
150	144	15	6	3	1	1243.9	1.764	87.4%	$77,662	$3,572,453	$41,821	$16,857	$13,200	-$10,324	Y	$3,650,115	0.5285
151	145	15	6	2	1	1282.3	1.901	87.6%	$74,838	$3,589,884	$37,520	$9,947	$11,700	-$10,335	Y	$3,664,722	0.5276
152	146	12	9	1	2	1394.8	1.986	90.0%	$50,199	$3,645,386	$40,800	-$10,046	$8,550	-$7,394	Y	$3,695,585	0.5260
153	147	14	11	1	2	1343.1	1.734	92.2%	$89,414	$3,644,242	$46,824	-$26,077	$7,050	-$14,166	Y	$3,733,656	0.5241
154	148	12	9	3	2	1375.3	1.975	89.6%	$59,201	$3,645,181	$46,279	-$1,244	$10,050	-$7,387	Y	$3,704,382	0.5233
155	149	15	8	1	2	1253.0	1.763	89.2%	$69,691	$3,640,478	$45,024	$2,101	$9,000	-$10,654	Y	$3,710,169	0.5227
156	150	12	9	2	2	1425.3	2.149	90.0%	$55,643	$3,667,647	$40,800	-$10,046	$8,550	-$7,401	Y	$3,723,289	0.5221
157	151	12	9	1	1	1377.7	1.986	89.6%	$52,152	$3,668,341	$41,120	-$6,412	$11,550	-$7,416	Y	$3,720,493	0.5216
158	152	14	11	3	2	1324.0	1.723	91.8%	$98,241	$3,644,040	$52,195	-$17,448	$8,550	-$14,159	Y	$3,742,281	0.5214
159	153	9	9	3	2	1577.0	2.343	89.5%	$56,200	$3,662,682	$48,002	$1,622	$10,050	-$5,955	Y	$3,718,882	0.5207
160	154	15	8	3	2	1237.7	1.754	88.9%	$76,759	$3,640,317	$49,325	$9,010	$10,500	-$10,648	Y	$3,717,076	0.5205
161	155	14	11	2	2	1373.1	1.894	92.2%	$94,752	$3,666,067	$46,824	-$26,077	$7,050	-$14,173	Y	$3,760,819	0.5203
162	156	9	9	1	1	1583.1	2.358	89.6%	$46,211	$3,685,346	$41,120	-$6,315	$11,550	-$5,991	Y	$3,731,558	0.5198
163	157	15	8	2	2	1276.9	1.891	89.2%	$73,965	$3,657,954	$45,024	$2,101	$9,000	-$10,659	Y	$3,731,919	0.5196
164	158	14	11	1	1	1327.8	1.734	91.8%	$91,418	$3,667,575	$47,144	-$22,444	$10,050	-$14,186	Y	$3,758,993	0.5196
165	159	12	9	3	1	1358.3	1.975	89.3%	$61,161	$3,668,152	$46,599	$2,389	$13,050	-$7,408	Y	$3,729,313	0.5189
166	160	15	8	1	1	1237.4	1.763	88.8%	$71,713	$3,663,768	$45,344	$5,734	$12,000	-$10,672	Y	$3,735,481	0.5182
167	161	12	9	2	1	1407.2	2.149	89.6%	$57,564	$3,690,356	$41,120	-$6,412	$11,550	-$7,423	Y	$3,747,920	0.5178
168	162	14	11	3	1	1308.7	1.723	91.5%	$100,251	$3,667,391	$52,516	-$13,814	$11,550	-$14,177	Y	$3,767,642	0.5170
169	163	9	9	3	1	1557.6	2.343	89.2%	$58,055	$3,685,099	$48,323	$5,256	$13,050	-$5,981	Y	$3,743,153	0.5164
170	164	15	8	3	1	1222.2	1.754	88.6%	$78,785	$3,663,620	$49,645	$12,644	$13,500	-$10,666	Y	$3,742,406	0.5161
171	165	14	11	2	1	1356.6	1.894	91.8%	$96,724	$3,689,161	$47,144	-$22,444	$10,050	-$14,194	Y	$3,785,885	0.5159
172	166	15	8	2	1	1260.5	1.891	88.8%	$75,962	$3,681,052	$45,344	$5,734	$12,000	-$10,677	Y	$3,757,013	0.5152
173	167	14	10	1	2	1445.4	1.734	92.5%	$90,322	$3,725,745	$42,845	-$32,946	$6,750	-$14,406	Y	$3,816,067	0.5137
174	168	14	10	3	2	1426.3	1.723	92.1%	$99,149	$3,725,544	$48,216	-$24,317	$8,250	-$14,399	Y	$3,824,693	0.5111
175	169	15	7	1	2	1392.7	1.763	89.5%	$70,959	$3,731,947	$41,045	-$4,768	$8,700	-$10,990	Y	$3,802,906	0.5109
176	170	14	10	2	2	1475.4	1.894	92.5%	$95,660	$3,747,571	$42,845	-$32,946	$6,750	-$14,413	Y	$3,843,230	0.5100
177	171	14	10	1	1	1430.1	1.734	92.1%	$92,301	$3,749,079	$43,165	-$29,313	$9,750	-$14,429	Y	$3,841,379	0.5094
178	172	15	7	3	2	1377.4	1.754	89.2%	$78,027	$3,731,785	$45,346	$2,142	$10,200	-$10,984	Y	$3,809,812	0.5089
179	173	13	6	1	2	1345.1	1.731	88.0%	$47,730	$3,755,419	$37,200	$6,350	$10,200	-$6,542	Y	$3,803,149	0.5086
180	174	15	7	2	2	1416.6	1.891	89.5%	$75,233	$3,749,422	$41,045	-$4,768	$8,700	-$10,995	Y	$3,824,655	0.5080
181	175	10	6	1	2	1459.3	2.041	88.0%	$40,707	$3,765,592	$37,200	$6,401	$10,200	-$5,157	Y	$3,806,300	0.5080

Database Analysis S

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	A	B	C	D	E	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO
1									Sensitivity analysis variables								
2									0%	0%	0%		0%	0%	# of successful designs		407
3	**All cases analysis (baseline)**					Constraints										MinWorth	Best Value
4						1600.0	2.7	85%	10000000	10000000	10000000	1000000	10000000	1000000		$1,939,384	0.9920
5		Technology Number				Mass	Length	Effeciency	System Unit	Development	20 yr Ops	20 yr Ops	20 yr Maint.	Recycling/	Successful		
6	Run #	Rotor	Motor/Gen	Bearings	Vac.	(kg)	(m)	(%)	cost ($)	cost ($)	cost ($)	cost+eff.	cost ($)	disposal cost ($)	design? (Y/N)	Worth ($)	Best Value
182	176	7	6	1	2	1542.0	2.070	88.0%	$40,669	$3,772,813	$37,200	$6,443	$10,200	-$4,945	Y	$3,813,482	0.5070
183	177	14	10	3	1	1411.0	1.723	91.8%	$101,134	$3,748,894	$48,537	-$20,683	$11,250	-$14,421	Y	$3,850,028	0.5069
184	178	15	7	1	1	1377.1	1.763	89.1%	$72,946	$3,755,237	$41,365	-$1,134	$11,700	-$11,011	Y	$3,828,183	0.5067
185	179	13	6	3	2	1327.5	1.721	87.7%	$55,853	$3,755,234	$42,143	$14,291	$11,700	-$6,535	Y	$3,811,086	0.5063
186	180	12	11	1	2	1364.5	1.971	92.2%	$51,775	$3,806,225	$46,824	-$26,071	$8,550	-$7,878	Y	$3,857,999	0.5060
187	181	14	10	2	1	1458.9	1.894	92.1%	$97,607	$3,770,664	$43,165	-$29,313	$9,750	-$14,435	Y	$3,868,271	0.5058
188	182	10	6	3	2	1438.5	2.030	87.6%	$50,325	$3,765,373	$43,053	$15,805	$11,700	-$5,149	Y	$3,815,699	0.5053
189	183	13	6	2	2	1372.6	1.878	88.0%	$52,642	$3,775,505	$37,200	$6,350	$10,200	-$6,548	Y	$3,828,146	0.5053
190	184	15	7	3	1	1361.9	1.754	88.9%	$80,019	$3,755,089	$45,666	$5,775	$13,200	-$11,005	Y	$3,835,108	0.5046
191	185	13	6	1	1	1329.7	1.731	87.6%	$49,733	$3,778,757	$37,520	$9,983	$13,200	-$6,560	Y	$3,828,490	0.5044
192	186	9	11	1	2	1572.3	2.343	92.2%	$45,941	$3,823,790	$46,824	-$25,974	$8,550	-$6,449	Y	$3,869,731	0.5043
193	187	10	6	2	2	1491.9	2.216	88.0%	$46,523	$3,789,376	$37,200	$6,401	$10,200	-$5,165	Y	$3,835,899	0.5041
194	188	7	6	3	2	1518.6	2.056	87.6%	$51,483	$3,772,566	$43,781	$17,016	$11,700	-$4,935	Y	$3,824,050	0.5040
195	189	10	6	1	1	1441.9	2.041	87.6%	$42,636	$3,788,464	$37,520	$10,035	$13,200	-$5,180	Y	$3,831,100	0.5038
196	190	15	7	2	1	1400.2	1.891	89.1%	$77,195	$3,772,520	$41,365	-$1,134	$11,700	-$11,017	Y	$3,849,715	0.5038
197	191	12	11	3	2	1345.0	1.960	91.8%	$60,777	$3,806,019	$52,302	-$17,270	$10,050	-$7,871	Y	$3,866,796	0.5035
198	192	7	6	1	1	1524.4	2.070	87.6%	$42,573	$3,795,642	$37,520	$10,076	$13,200	-$4,968	Y	$3,838,215	0.5029
199	193	7	6	2	2	1578.6	2.265	88.0%	$47,209	$3,799,554	$37,200	$6,443	$10,200	-$4,953	Y	$3,846,762	0.5026
200	194	12	11	2	2	1395.0	2.134	92.2%	$57,219	$3,828,485	$46,824	-$26,071	$8,550	-$7,885	Y	$3,885,704	0.5024
201	195	13	6	3	1	1312.2	1.721	87.3%	$57,862	$3,778,587	$42,464	$17,925	$14,700	-$6,555	Y	$3,836,449	0.5021
202	196	12	11	1	1	1347.5	1.971	91.8%	$53,737	$3,829,202	$47,144	-$22,438	$11,550	-$7,898	Y	$3,882,939	0.5019
203	197	10	6	3	1	1421.2	2.030	87.3%	$52,261	$3,788,262	$43,374	$19,438	$14,700	-$5,171	Y	$3,840,524	0.5012
204	198	13	6	2	1	1356.3	1.878	87.6%	$54,617	$3,798,621	$37,520	$9,983	$13,200	-$6,567	Y	$3,853,238	0.5012
205	199	9	11	3	2	1546.7	2.328	91.7%	$57,776	$3,823,520	$54,026	-$14,403	$10,050	-$6,439	Y	$3,881,296	0.5011
206	200	9	11	1	1	1552.9	2.343	91.8%	$47,797	$3,846,208	$47,144	-$22,340	$11,550	-$6,473	Y	$3,894,004	0.5003
207	201	10	6	2	1	1473.3	2.216	87.6%	$48,418	$3,811,985	$37,520	$10,035	$13,200	-$5,187	Y	$3,860,403	0.5000
208	202	7	6	3	1	1501.1	2.056	87.2%	$53,395	$3,795,415	$44,102	$20,649	$14,700	-$4,959	Y	$3,848,811	0.4999
209	203	12	11	3	1	1328.1	1.960	91.5%	$62,746	$3,829,014	$52,623	-$13,636	$13,050	-$7,889	Y	$3,891,760	0.4994
210	204	7	6	2	1	1559.7	2.265	87.6%	$49,075	$3,822,088	$37,520	$10,076	$13,200	-$4,978	Y	$3,871,163	0.4986
211	205	12	11	2	1	1377.0	2.134	91.8%	$59,149	$3,851,217	$47,144	-$22,438	$11,550	-$7,906	Y	$3,910,367	0.4984
212	206	13	8	1	2	1323.3	1.721	89.2%	$48,846	$3,846,571	$45,024	$2,137	$10,500	-$6,885	Y	$3,895,417	0.4971
213	207	9	11	3	1	1527.4	2.328	91.4%	$59,640	$3,845,960	$54,346	-$10,769	$13,050	-$6,462	Y	$3,905,600	0.4971
214	208	10	8	1	2	1437.5	2.031	89.2%	$41,824	$3,856,745	$45,024	$2,189	$10,500	-$5,500	Y	$3,898,568	0.4965
215	209	12	10	1	2	1466.8	1.971	92.5%	$52,682	$3,887,728	$42,845	-$32,940	$8,250	-$8,118	Y	$3,940,410	0.4963
216	210	9	11	2	1	1591.6	2.557	91.8%	$54,911	$3,875,149	$47,144	-$22,340	$11,550	-$6,482	Y	$3,930,060	0.4957

Database Analysis S

Ready 95%

	A	B	C	D	E	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO
1									Sensitivity analysis variables								
2									0%	0%	0%		0%	0%	# of successful designs		407
3	**All cases analysis (baseline)**					Constraints										MinWorth	Best Value
4						1600.0	2.7	85%	10000000	10000000	10000000	1000000	10000000	1000000		$1,939,384	0.9920
5		Technology Number				Mass	Length	Effeciency	System Unit	Development	20 yr Ops	20 yr Ops	20 yr Maint.	Recycling/	Successful		
6	Run #	Rotor	Motor/Gen	Bearings	Vac.	(kg)	(m)	(%)	cost ($)	cost ($)	cost ($)	cost+eff.	cost ($)	disposal cost ($)	design? (Y/N)	Worth ($)	Best Value
217	211	7	8	1	2	1520.1	2.060	89.2%	$41,785	$3,863,965	$45,024	$2,230	$10,500	-$5,288	Y	$3,905,750	0.4956
218	212	13	8	3	2	1305.7	1.711	88.9%	$56,969	$3,846,386	$49,967	$10,079	$12,000	-$6,878	Y	$3,903,355	0.4949
219	213	10	8	3	2	1416.7	2.020	88.8%	$51,442	$3,856,526	$50,877	$11,592	$12,000	-$5,492	Y	$3,907,967	0.4940
220	214	13	8	2	2	1350.8	1.868	89.2%	$53,758	$3,866,657	$45,024	$2,137	$10,500	-$6,891	Y	$3,920,415	0.4940
221	215	12	10	3	2	1447.3	1.960	92.1%	$61,685	$3,887,523	$48,323	-$24,139	$9,750	-$8,110	Y	$3,949,208	0.4939
222	216	13	8	1	1	1308.0	1.721	88.8%	$50,857	$3,869,924	$45,344	$5,771	$13,500	-$6,903	Y	$3,920,781	0.4931
223	217	12	10	2	2	1497.3	2.134	92.5%	$58,127	$3,909,988	$42,845	-$32,940	$8,250	-$8,125	Y	$3,968,115	0.4928
224	218	10	8	2	2	1470.1	2.206	89.2%	$47,640	$3,880,528	$45,024	$2,189	$10,500	-$5,508	Y	$3,928,168	0.4928
225	219	7	8	3	2	1496.7	2.046	88.8%	$52,600	$3,863,719	$51,605	$12,803	$12,000	-$5,278	Y	$3,916,318	0.4927
226	220	10	8	1	1	1420.1	2.031	88.8%	$43,759	$3,879,631	$45,344	$5,822	$13,500	-$5,522	Y	$3,923,391	0.4926
227	221	12	10	1	1	1449.8	1.971	92.1%	$54,620	$3,910,705	$43,165	-$29,306	$11,250	-$8,140	Y	$3,965,326	0.4923
228	222	7	8	1	1	1502.6	2.060	88.8%	$43,697	$3,886,809	$45,344	$5,864	$13,500	-$5,310	Y	$3,930,506	0.4917
229	223	7	8	2	2	1556.8	2.255	89.2%	$48,325	$3,890,706	$45,024	$2,230	$10,500	-$5,296	Y	$3,939,031	0.4914
230	224	13	8	3	1	1290.5	1.711	88.5%	$58,986	$3,869,754	$50,287	$13,712	$15,000	-$6,898	Y	$3,928,740	0.4909
231	225	16	5	1	2	1266.7	1.534	87.2%	$71,645	$3,862,147	$41,424	$18,528	$10,650	-$10,341	Y	$3,933,792	0.4907
232	226	10	8	3	1	1399.4	2.020	88.5%	$53,385	$3,879,430	$51,197	$15,226	$15,000	-$5,514	Y	$3,932,814	0.4900
233	227	13	8	2	1	1334.5	1.868	88.8%	$55,740	$3,889,789	$45,344	$5,771	$13,500	-$6,910	Y	$3,945,529	0.4900
234	228	12	10	3	1	1430.4	1.960	91.8%	$63,629	$3,910,517	$48,644	-$20,505	$12,750	-$8,132	Y	$3,974,146	0.4900
235	229	10	8	2	1	1451.6	2.206	88.8%	$49,542	$3,903,152	$45,344	$5,822	$13,500	-$5,529	Y	$3,952,694	0.4889
236	230	12	10	2	1	1479.3	2.134	92.1%	$60,032	$3,932,721	$43,165	-$29,306	$11,250	-$8,147	Y	$3,992,753	0.4889
237	231	7	8	3	1	1479.3	2.046	88.4%	$54,519	$3,886,583	$51,925	$16,437	$15,000	-$5,302	Y	$3,941,102	0.4889
238	232	16	5	3	2	1251.3	1.525	86.9%	$78,747	$3,861,985	$45,746	$25,472	$12,150	-$10,335	Y	$3,940,733	0.4888
239	233	16	5	2	2	1290.7	1.662	87.2%	$75,940	$3,879,710	$41,424	$18,528	$10,650	-$10,347	Y	$3,955,650	0.4880
240	234	7	8	2	1	1537.9	2.255	88.8%	$50,198	$3,913,256	$45,344	$5,864	$13,500	-$5,321	Y	$3,963,453	0.4876
241	235	16	5	1	1	1252.6	1.534	86.8%	$73,697	$3,885,783	$41,744	$22,162	$13,650	-$10,359	Y	$3,959,480	0.4867
242	236	13	7	1	2	1463.0	1.721	89.5%	$50,114	$3,938,040	$41,045	-$4,731	$10,200	-$7,221	Y	$3,988,154	0.4865
243	237	10	7	1	2	1577.2	2.031	89.5%	$43,091	$3,948,213	$41,045	-$4,680	$10,200	-$5,836	Y	$3,991,305	0.4859
244	238	16	5	3	1	1237.3	1.525	86.6%	$80,805	$3,885,634	$46,066	$29,106	$15,150	-$10,353	Y	$3,966,439	0.4848
245	239	13	7	3	2	1445.4	1.711	89.2%	$58,237	$3,937,855	$45,988	$3,210	$11,700	-$7,214	Y	$3,996,092	0.4844
246	240	16	5	2	1	1275.8	1.662	86.8%	$77,967	$3,903,152	$41,744	$22,162	$13,650	-$10,365	Y	$3,981,119	0.4841
247	241	10	7	3	2	1556.4	2.020	89.1%	$52,710	$3,947,994	$46,898	$4,724	$11,700	-$5,828	Y	$4,000,704	0.4835
248	242	13	7	2	2	1490.5	1.868	89.5%	$55,026	$3,958,126	$41,045	-$4,731	$10,200	-$7,227	Y	$4,013,152	0.4835
249	243	13	7	1	1	1447.7	1.721	89.1%	$52,090	$3,961,393	$41,365	-$1,098	$13,200	-$7,242	Y	$4,013,483	0.4826
250	244	10	7	1	1	1559.8	2.031	89.1%	$44,993	$3,971,100	$41,365	-$1,046	$13,200	-$5,861	Y	$4,016,093	0.4821
251	245	16	4	1	2	1443.2	1.534	87.5%	$73,267	$3,950,372	$37,445	$11,659	$10,350	-$10,772	Y	$4,023,639	0.4807

Database | Analysis | S

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3	**All cases analysis (baseline)**					Constraints										MinWorth	Best Value
4						1600.0	2.7	85%	10000000	10000000	10000000	1000000	10000000	1000000		$1,939,384	0.9920
5		Technology Number				Mass	Length	Effeciency	System Unit	Development	20 yr Ops	20 yr Ops	20 yr Maint.	Recycling/	Successful		
6	Run #	Rotor	Motor/Gen	Bearings	Vac.	(kg)	(m)	(%)	cost ($)	cost ($)	cost ($)	cost+eff.	cost ($)	disposal cost ($)	design? (Y/N)	Worth ($)	Best Value
252	246	13	7	3	1	1430.2	1.711	88.8%	$60,219	$3,961,223	$46,309	$6,844	$14,700	-$7,235	Y	$4,021,442	0.4806
253	247	10	7	3	1	1539.1	2.020	88.8%	$54,618	$3,970,898	$47,219	$8,357	$14,700	-$5,852	Y	$4,025,516	0.4797
254	248	13	7	2	1	1474.2	1.868	89.1%	$56,973	$3,981,258	$41,365	-$1,098	$13,200	-$7,250	Y	$4,038,231	0.4797
255	249	16	4	3	2	1427.8	1.525	87.2%	$80,369	$3,950,210	$41,767	$18,603	$11,850	-$10,766	Y	$4,030,580	0.4788
256	250	10	7	2	1	1591.3	2.206	89.1%	$50,775	$3,994,621	$41,365	-$1,046	$13,200	-$5,869	Y	$4,045,396	0.4787
257	251	16	4	2	2	1467.3	1.662	87.5%	$77,562	$3,967,935	$37,445	$11,659	$10,350	-$10,777	Y	$4,045,497	0.4781
258	252	16	4	1	1	1429.1	1.534	87.1%	$75,276	$3,974,008	$37,765	$15,293	$13,350	-$10,794	Y	$4,049,284	0.4768
259	253	16	4	3	1	1413.8	1.525	86.9%	$82,384	$3,973,859	$42,088	$22,237	$14,850	-$10,788	Y	$4,056,243	0.4750
260	254	16	4	2	1	1452.4	1.662	87.1%	$79,546	$3,991,377	$37,765	$15,293	$13,350	-$10,801	Y	$4,070,923	0.4743
261	255	15	9	1	2	1254.1	1.763	90.0%	$69,787	$4,084,580	$40,800	-$10,113	$9,300	-$10,683	Y	$4,154,367	0.4681
262	256	15	9	3	2	1238.8	1.754	89.7%	$76,855	$4,084,419	$45,101	-$3,203	$10,800	-$10,676	Y	$4,161,274	0.4664
263	257	15	9	2	2	1278.0	1.891	90.0%	$74,061	$4,102,056	$40,800	-$10,113	$9,300	-$10,688	Y	$4,176,117	0.4657
264	258	14	12	1	2	1344.2	1.734	93.0%	$89,510	$4,124,368	$42,600	-$38,291	$7,350	-$14,195	Y	$4,213,878	0.4652
265	259	15	9	1	1	1238.5	1.763	89.6%	$71,809	$4,107,871	$41,120	-$6,479	$12,300	-$10,701	Y	$4,179,679	0.4645
266	260	14	12	3	2	1325.1	1.723	92.6%	$98,337	$4,124,166	$47,972	-$29,661	$8,850	-$14,187	Y	$4,222,503	0.4631
267	261	15	9	3	1	1223.3	1.754	89.4%	$78,881	$4,107,723	$45,421	$431	$13,800	-$10,694	Y	$4,186,604	0.4628
268	262	14	12	2	2	1374.2	1.894	93.0%	$94,848	$4,146,193	$42,600	-$38,291	$7,350	-$14,201	Y	$4,241,041	0.4622
269	263	15	9	2	1	1261.6	1.891	89.6%	$76,057	$4,125,154	$41,120	-$6,479	$12,300	-$10,706	Y	$4,201,211	0.4622
270	264	14	12	1	1	1328.9	1.734	92.6%	$91,514	$4,147,701	$42,920	-$34,657	$10,350	-$14,215	Y	$4,239,215	0.4617
271	265	14	12	3	1	1309.8	1.723	92.3%	$100,347	$4,147,517	$48,292	-$26,028	$11,850	-$14,207	Y	$4,247,863	0.4596
272	266	14	12	2	1	1357.7	1.894	92.6%	$96,820	$4,169,287	$42,920	-$34,657	$10,350	-$14,223	Y	$4,266,107	0.4587
273	267	15	11	1	2	1223.8	1.748	92.2%	$71,363	$4,245,419	$46,824	-$26,138	$9,300	-$11,166	Y	$4,316,782	0.4522
274	268	12	12	1	2	1365.6	1.971	93.0%	$51,871	$4,286,351	$42,600	-$38,285	$8,850	-$7,907	Y	$4,338,221	0.4509
275	269	15	11	3	2	1208.5	1.739	91.9%	$78,431	$4,245,258	$51,125	-$19,229	$10,800	-$11,160	Y	$4,323,688	0.4506
276	270	15	11	2	2	1247.7	1.876	92.2%	$75,637	$4,262,894	$46,824	-$26,138	$9,300	-$11,172	Y	$4,338,531	0.4499
277	271	9	12	1	2	1573.4	2.343	93.0%	$46,037	$4,303,916	$42,600	-$38,187	$8,850	-$6,477	Y	$4,349,953	0.4495
278	272	12	12	3	2	1346.1	1.960	92.6%	$60,873	$4,286,145	$48,079	-$29,483	$10,350	-$7,899	Y	$4,347,019	0.4489
279	273	15	11	1	1	1208.3	1.748	91.8%	$73,394	$4,268,732	$47,144	-$22,505	$12,300	-$11,184	Y	$4,342,126	0.4489
280	274	12	12	2	2	1396.1	2.134	93.0%	$57,315	$4,308,611	$42,600	-$38,285	$8,850	-$7,913	Y	$4,365,926	0.4480
281	275	12	12	1	1	1348.6	1.971	92.6%	$53,833	$4,309,328	$42,920	-$34,651	$11,850	-$7,927	Y	$4,363,161	0.4476
282	276	13	9	1	2	1324.4	1.721	90.0%	$48,942	$4,290,673	$40,800	-$10,076	$10,800	-$6,913	Y	$4,339,616	0.4475
283	277	15	11	3	1	1193.1	1.739	91.6%	$80,467	$4,268,584	$51,445	-$15,595	$13,800	-$11,177	Y	$4,349,050	0.4473
284	278	10	9	1	2	1438.6	2.031	90.0%	$41,920	$4,300,847	$40,800	-$10,025	$10,800	-$5,529	Y	$4,342,767	0.4471
285	279	9	12	3	2	1547.8	2.328	92.5%	$57,872	$4,303,646	$49,802	-$26,617	$10,350	-$6,467	Y	$4,361,518	0.4470
286	280	15	11	2	1	1231.4	1.876	91.8%	$77,643	$4,286,015	$47,144	-$22,505	$12,300	-$11,188	Y	$4,363,658	0.4466

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4						1600.0	2.7	85%	10000000	10000000	10000000	1000000	10000000	1000000		$1,939,384	0.9920
5		Technology Number				Mass	Length	Effeciency	System Unit	Development	20 yr Ops	20 yr Ops	20 yr Maint.	Recycling/	Successful		
6	Run #	Rotor	Motor/Gen	Bearings	Vac.	(kg)	(m)	(%)	cost ($)	cost ($)	cost ($)	cost+eff.	cost ($)	disposal cost ($)	design? (Y/N)	Worth ($)	Best Value
287	281	9	12	1	1	1554.0	2.343	92.6%	$47,893	$4,326,334	$42,920	-$34,554	$11,850	-$6,501	Y	$4,374,226	0.4463
288	282	7	9	1	2	1521.2	2.060	90.0%	$41,881	$4,308,067	$40,800	-$9,983	$10,800	-$5,316	Y	$4,349,949	0.4463
289	283	13	9	3	2	1306.8	1.711	89.7%	$57,065	$4,290,488	$45,743	-$2,135	$12,300	-$6,906	Y	$4,347,553	0.4458
290	284	12	12	3	1	1329.2	1.960	92.3%	$62,842	$4,309,140	$48,399	-$25,850	$13,350	-$7,920	Y	$4,371,982	0.4457
291	285	16	6	1	2	1267.8	1.534	88.0%	$71,741	$4,279,611	$37,200	$6,315	$10,950	-$10,370	Y	$4,351,352	0.4450
292	286	10	9	3	2	1417.8	2.020	89.6%	$51,538	$4,300,628	$46,653	-$621	$12,300	-$5,521	Y	$4,352,166	0.4450
293	287	13	9	2	2	1351.9	1.868	90.0%	$53,854	$4,310,759	$40,800	-$10,076	$10,800	-$6,919	Y	$4,364,613	0.4450
294	288	12	12	2	1	1378.1	2.134	92.6%	$59,245	$4,331,344	$42,920	-$34,651	$11,850	-$7,935	Y	$4,390,589	0.4448
295	289	15	10	1	2	1326.1	1.748	92.5%	$72,271	$4,326,922	$42,845	-$33,007	$9,000	-$11,406	Y	$4,399,193	0.4444
296	290	13	9	1	1	1309.1	1.721	89.6%	$50,953	$4,314,026	$41,120	-$6,443	$13,800	-$6,932	Y	$4,364,979	0.4443
297	291	10	9	2	2	1471.2	2.206	90.0%	$47,736	$4,324,630	$40,800	-$10,025	$10,800	-$5,536	Y	$4,372,366	0.4440
298	292	7	9	3	2	1497.8	2.046	89.6%	$52,696	$4,307,821	$47,381	$590	$12,300	-$5,307	Y	$4,360,517	0.4440
299	293	10	9	1	1	1421.2	2.031	89.6%	$43,855	$4,323,733	$41,120	-$6,391	$13,800	-$5,550	Y	$4,367,589	0.4439
300	294	9	12	3	1	1528.5	2.328	92.2%	$59,736	$4,326,086	$50,123	-$22,983	$13,350	-$6,492	Y	$4,385,822	0.4438
301	295	16	6	3	2	1252.4	1.525	87.7%	$78,843	$4,279,449	$41,522	$13,259	$12,450	-$10,364	Y	$4,358,293	0.4434
302	296	7	9	1	1	1503.7	2.060	89.6%	$43,792	$4,330,911	$41,120	-$6,350	$13,800	-$5,339	Y	$4,374,704	0.4431
303	297	7	9	2	2	1557.9	2.255	90.0%	$48,421	$4,334,808	$40,800	-$9,983	$10,800	-$5,324	Y	$4,383,229	0.4429
304	298	15	10	3	2	1310.8	1.739	92.2%	$79,339	$4,326,761	$47,146	-$26,097	$10,500	-$11,400	Y	$4,406,099	0.4429
305	299	16	6	2	2	1291.8	1.662	88.0%	$76,036	$4,297,174	$37,200	$6,315	$10,950	-$10,375	Y	$4,373,210	0.4428
306	300	9	12	2	1	1592.7	2.557	92.6%	$55,007	$4,355,275	$42,920	-$34,554	$11,850	-$6,512	Y	$4,410,282	0.4427
307	301	13	9	3	1	1291.6	1.711	89.3%	$59,081	$4,313,856	$46,064	$1,499	$15,300	-$6,926	Y	$4,372,938	0.4425
308	302	15	10	2	2	1350.0	1.876	92.5%	$76,545	$4,344,398	$42,845	-$33,007	$9,000	-$11,412	Y	$4,420,943	0.4422
309	303	10	9	3	1	1400.5	2.020	89.3%	$53,480	$4,323,532	$46,974	$3,012	$15,300	-$5,542	Y	$4,377,012	0.4418
310	304	13	9	2	1	1335.6	1.868	89.6%	$55,836	$4,333,891	$41,120	-$6,443	$13,800	-$6,940	Y	$4,389,727	0.4418
311	305	16	6	1	1	1253.7	1.534	87.6%	$73,793	$4,303,247	$37,520	$9,948	$13,950	-$10,389	Y	$4,377,040	0.4417
312	306	15	10	1	1	1310.6	1.748	92.1%	$74,277	$4,350,235	$43,165	-$29,373	$12,000	-$11,426	Y	$4,424,512	0.4412
313	307	10	9	2	1	1452.7	2.206	89.6%	$49,637	$4,347,254	$41,120	-$6,391	$13,800	-$5,558	Y	$4,396,892	0.4409
314	308	7	9	3	1	1480.4	2.046	89.2%	$54,615	$4,330,685	$47,702	$4,223	$15,300	-$5,331	Y	$4,385,299	0.4408
315	309	16	6	3	1	1238.4	1.525	87.4%	$80,901	$4,303,098	$41,843	$16,892	$15,450	-$10,381	Y	$4,383,999	0.4402
316	310	7	9	2	1	1539.0	2.255	89.6%	$50,294	$4,357,358	$41,120	-$6,350	$13,800	-$5,349	Y	$4,407,651	0.4398
317	311	15	10	3	1	1295.4	1.739	91.9%	$81,349	$4,350,087	$47,466	-$22,464	$13,500	-$11,420	Y	$4,431,437	0.4397
318	312	16	6	2	1	1276.9	1.662	87.6%	$78,063	$4,320,616	$37,520	$9,948	$13,950	-$10,394	Y	$4,398,679	0.4396
319	313	15	10	2	1	1333.7	1.876	92.1%	$78,526	$4,367,518	$43,165	-$29,373	$12,000	-$11,433	Y	$4,446,044	0.4390
320	314	16	8	1	2	1245.9	1.524	89.2%	$72,857	$4,370,764	$45,024	$2,102	$11,250	-$10,713	Y	$4,443,621	0.4362
321	315	16	8	3	2	1230.5	1.515	88.9%	$79,960	$4,370,602	$49,346	$9,046	$12,750	-$10,707	Y	$4,450,562	0.4347

Database | Analysis | S

Ready 95%

	A	B	C	D	E	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO
1									Sensitivity analysis variables								
2									0%	0%	0%		0%	0%		# of successful designs	407
3	All cases analysis (baseline)					Constraints										MinWorth	Best Value
4						1600.0	2.7	85%	10000000	10000000	10000000	1000000	10000000	1000000		$1,939,384	0.9920
5		Technology Number				Mass	Length	Effeciency	System Unit	Development	20 yr Ops	20 yr Ops	20 yr Maint.	Recycling/	Successful		
6	Run #	Rotor	Motor/Gen	Bearings	Vac.	(kg)	(m)	(%)	cost ($)	cost ($)	cost ($)	cost+eff.	cost ($)	disposal cost ($)	design? (Y/N)	Worth ($)	Best Value
322	316	16	8	2	2	1270.0	1.652	89.2%	$77,153	$4,388,326	$45,024	$2,102	$11,250	-$10,718	Y	$4,465,479	0.4340
323	317	16	8	1	1	1231.9	1.524	88.8%	$74,917	$4,394,414	$45,344	$5,736	$14,250	-$10,731	Y	$4,469,331	0.4330
324	318	13	11	1	2	1294.1	1.706	92.2%	$50,518	$4,451,512	$46,824	-$26,102	$10,800	-$7,397	Y	$4,502,030	0.4330
325	319	10	11	1	2	1408.3	2.016	92.2%	$43,495	$4,461,686	$46,824	-$26,050	$10,800	-$6,013	Y	$4,505,181	0.4325
326	320	7	11	1	2	1490.9	2.045	92.2%	$43,457	$4,468,906	$46,824	-$26,009	$10,800	-$5,800	Y	$4,512,363	0.4318
327	321	16	8	3	1	1216.6	1.515	88.6%	$82,024	$4,394,265	$49,666	$12,680	$15,750	-$10,725	Y	$4,476,290	0.4316
328	322	13	11	3	2	1276.5	1.696	91.9%	$58,641	$4,451,327	$51,767	-$18,160	$12,300	-$7,390	Y	$4,509,968	0.4313
329	323	16	8	2	1	1255.1	1.652	88.8%	$79,186	$4,411,783	$45,344	$5,736	$14,250	-$10,737	Y	$4,490,970	0.4310
330	324	10	11	3	2	1387.5	2.005	91.8%	$53,114	$4,461,466	$52,677	-$16,647	$12,300	-$6,005	Y	$4,514,580	0.4306
331	325	13	11	2	2	1321.6	1.853	92.2%	$55,430	$4,471,598	$46,824	-$26,102	$10,800	-$7,403	Y	$4,527,028	0.4306
332	326	13	11	1	1	1278.9	1.706	91.8%	$52,538	$4,474,888	$47,144	-$22,468	$13,800	-$7,416	Y	$4,527,426	0.4299
333	327	10	11	2	2	1440.9	2.191	92.2%	$49,312	$4,485,469	$46,824	-$26,050	$10,800	-$6,020	Y	$4,534,780	0.4297
334	328	7	11	3	2	1467.5	2.031	91.8%	$54,272	$4,468,659	$53,405	-$15,436	$12,300	-$5,791	Y	$4,522,931	0.4296
335	329	10	11	1	1	1391.0	2.016	91.8%	$45,441	$4,484,594	$47,144	-$22,417	$13,800	-$6,033	Y	$4,530,035	0.4295
336	330	7	11	1	1	1473.5	2.045	91.8%	$45,378	$4,491,772	$47,144	-$22,375	$13,800	-$5,822	Y	$4,537,150	0.4288
337	331	7	11	2	2	1527.6	2.240	92.2%	$49,997	$4,495,647	$46,824	-$26,009	$10,800	-$5,808	Y	$4,545,644	0.4286
338	332	13	11	3	1	1261.4	1.696	91.5%	$60,667	$4,474,718	$52,087	-$14,527	$15,300	-$7,409	Y	$4,535,384	0.4282
339	333	16	7	1	2	1385.6	1.524	89.5%	$74,125	$4,462,232	$41,045	-$4,767	$10,950	-$11,049	Y	$4,536,357	0.4280
340	334	10	11	3	1	1370.3	2.005	91.5%	$55,066	$4,484,393	$52,997	-$13,013	$15,300	-$6,026	Y	$4,539,459	0.4276
341	335	13	11	2	1	1305.4	1.853	91.8%	$57,421	$4,494,752	$47,144	-$22,468	$13,800	-$7,422	Y	$4,552,173	0.4275
342	336	10	11	2	1	1422.5	2.191	91.8%	$51,223	$4,508,116	$47,144	-$22,417	$13,800	-$6,041	Y	$4,559,338	0.4267
343	337	7	11	3	1	1450.2	2.031	91.4%	$56,200	$4,491,546	$53,725	-$11,802	$15,300	-$5,814	Y	$4,547,746	0.4267
344	338	16	7	3	2	1370.2	1.515	89.2%	$81,228	$4,462,070	$45,367	$2,177	$12,450	-$11,043	Y	$4,543,298	0.4265
345	339	16	7	2	2	1409.7	1.652	89.5%	$78,420	$4,479,795	$41,045	-$4,767	$10,950	-$11,054	Y	$4,558,215	0.4259
346	340	13	10	1	2	1396.4	1.706	92.5%	$51,426	$4,533,015	$42,845	-$32,970	$10,500	-$7,637	Y	$4,584,441	0.4258
347	341	7	11	2	1	1508.8	2.240	91.8%	$51,879	$4,518,219	$47,144	-$22,375	$13,800	-$5,831	Y	$4,570,098	0.4257
348	342	10	10	1	2	1510.6	2.016	92.5%	$44,403	$4,543,189	$42,845	-$32,919	$10,500	-$6,253	Y	$4,587,592	0.4254
349	343	16	7	1	1	1371.6	1.524	89.1%	$76,150	$4,485,883	$41,365	-$1,133	$13,950	-$11,069	Y	$4,562,033	0.4250
350	344	7	10	1	2	1593.2	2.045	92.5%	$44,365	$4,550,409	$42,845	-$32,877	$10,500	-$6,040	Y	$4,594,774	0.4247
351	345	13	10	3	2	1378.8	1.696	92.2%	$59,549	$4,532,830	$47,788	-$25,029	$12,000	-$7,630	Y	$4,592,379	0.4242
352	346	16	7	3	1	1356.3	1.515	88.9%	$83,258	$4,485,734	$45,688	$5,811	$15,450	-$11,063	Y	$4,568,992	0.4235
353	347	10	10	3	2	1489.8	2.005	92.1%	$54,022	$4,542,970	$48,698	-$23,515	$12,000	-$6,244	Y	$4,596,991	0.4235
354	348	13	10	2	2	1423.9	1.853	92.5%	$56,338	$4,553,101	$42,845	-$32,970	$10,500	-$7,643	Y	$4,609,439	0.4235
355	349	16	7	2	1	1394.8	1.652	89.1%	$80,420	$4,503,252	$41,365	-$1,133	$13,950	-$11,076	Y	$4,583,672	0.4229
356	350	13	10	1	1	1381.2	1.706	92.1%	$53,421	$4,556,391	$43,165	-$29,337	$13,500	-$7,657	Y	$4,609,812	0.4229

Database | Analysis

Ready 95%

	A	B	C	D	E	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO
1									Sensitivity analysis variables								
2									0%	0%	0%		0%	0%		# of successful designs	407
3	All cases analysis (baseline)					Constraints										MinWorth	Best Value
4						1600.0	2.7	85%	10000000	10000000	10000000	1000000	10000000	1000000		$1,939,384	0.9920
5		Technology Number				Mass	Length	Effeciency	System Unit	Development	20 yr Ops	20 yr Ops	20 yr Maint.	Recycling/	Successful		
6	Run #	Rotor	Motor/Gen	Bearings	Vac.	(kg)	(m)	(%)	cost ($)	cost ($)	cost ($)	cost+eff.	cost ($)	disposal cost ($)	design? (Y/N)	Worth ($)	Best Value
357	351	10	10	2	2	1543.2	2.191	92.5%	$50,220	$4,566,972	$42,845	-$32,919	$10,500	-$6,260	Y	$4,617,192	0.4227
358	352	7	10	3	2	1569.8	2.031	92.1%	$55,179	$4,550,163	$49,426	-$22,305	$12,000	-$6,031	Y	$4,605,342	0.4226
359	353	10	10	1	1	1493.3	2.016	92.1%	$46,323	$4,566,098	$43,165	-$29,285	$13,500	-$6,275	Y	$4,612,421	0.4225
360	354	7	10	1	1	1575.8	2.045	92.1%	$46,261	$4,573,276	$43,165	-$29,244	$13,500	-$6,066	Y	$4,619,536	0.4218
361	355	13	10	3	1	1363.7	1.696	91.8%	$61,549	$4,556,221	$48,109	-$21,395	$15,000	-$7,650	Y	$4,617,770	0.4213
362	356	10	10	3	1	1472.6	2.005	91.8%	$55,949	$4,565,896	$49,019	-$19,882	$15,000	-$6,267	Y	$4,621,845	0.4206
363	357	13	10	2	1	1407.7	1.853	92.1%	$58,304	$4,576,255	$43,165	-$29,337	$13,500	-$7,664	Y	$4,634,559	0.4206
364	358	10	10	2	1	1524.8	2.191	92.1%	$52,106	$4,589,619	$43,165	-$29,285	$13,500	-$6,283	Y	$4,641,724	0.4198
365	359	7	10	3	1	1552.5	2.031	91.7%	$57,083	$4,573,049	$49,747	-$18,671	$15,000	-$6,057	Y	$4,630,132	0.4197
366	360	15	12	1	2	1224.9	1.748	93.0%	$71,459	$4,725,545	$42,600	-$38,352	$9,600	-$11,195	Y	$4,797,004	0.4077
367	361	15	12	3	2	1209.6	1.739	92.7%	$78,527	$4,725,384	$46,901	-$31,442	$11,100	-$11,189	Y	$4,803,910	0.4064
368	362	15	12	2	2	1248.8	1.876	93.0%	$75,733	$4,743,020	$42,600	-$38,352	$9,600	-$11,200	Y	$4,818,754	0.4058
369	363	15	12	1	1	1209.4	1.748	92.6%	$73,490	$4,748,858	$42,920	-$34,718	$12,600	-$11,213	Y	$4,822,348	0.4050
370	364	15	12	3	1	1194.2	1.739	92.4%	$80,562	$4,748,710	$47,221	-$27,808	$14,100	-$11,207	Y	$4,829,272	0.4037
371	365	15	12	2	1	1232.5	1.876	92.6%	$77,739	$4,766,141	$42,920	-$34,718	$12,600	-$11,219	Y	$4,843,880	0.4032
372	366	16	9	1	2	1247.0	1.524	90.0%	$72,953	$4,814,866	$40,800	-$10,111	$11,550	-$10,741	Y	$4,887,819	0.3975
373	367	16	9	3	2	1231.6	1.515	89.7%	$80,056	$4,814,704	$45,122	-$3,167	$13,050	-$10,735	Y	$4,894,760	0.3963
374	368	16	9	2	2	1271.1	1.652	90.0%	$77,249	$4,832,428	$40,800	-$10,111	$11,550	-$10,747	Y	$4,909,677	0.3958
375	369	16	9	1	1	1233.0	1.524	89.6%	$75,012	$4,838,516	$41,120	-$6,478	$14,550	-$10,760	Y	$4,913,529	0.3949
376	370	16	9	3	1	1217.7	1.515	89.4%	$82,120	$4,838,367	$45,443	$466	$16,050	-$10,754	Y	$4,920,488	0.3937
377	371	16	9	2	1	1256.2	1.652	89.6%	$79,282	$4,855,885	$41,120	-$6,478	$14,550	-$10,766	Y	$4,935,168	0.3932
378	372	13	12	1	2	1295.2	1.706	93.0%	$50,614	$4,931,638	$42,600	-$38,315	$11,100	-$7,426	Y	$4,982,252	0.3920
379	373	10	12	1	2	1409.4	2.016	93.0%	$43,591	$4,941,812	$42,600	-$38,264	$11,100	-$6,041	Y	$4,985,403	0.3916
380	374	7	12	1	2	1492.0	2.045	93.0%	$43,553	$4,949,032	$42,600	-$38,222	$11,100	-$5,829	Y	$4,992,585	0.3910
381	375	13	12	3	2	1277.6	1.696	92.7%	$58,737	$4,931,453	$47,543	-$30,374	$12,600	-$7,419	Y	$4,990,190	0.3906
382	376	10	12	3	2	1388.6	2.005	92.6%	$53,210	$4,941,592	$48,453	-$28,860	$12,600	-$6,033	Y	$4,994,802	0.3900
383	377	13	12	2	2	1322.7	1.853	93.0%	$55,526	$4,951,724	$42,600	-$38,315	$11,100	-$7,432	Y	$5,007,250	0.3900
384	378	13	12	1	1	1280.0	1.706	92.6%	$52,634	$4,955,014	$42,920	-$34,682	$14,100	-$7,444	Y	$5,007,648	0.3895
385	379	10	12	2	2	1442.0	2.191	93.0%	$49,408	$4,965,595	$42,600	-$38,264	$11,100	-$6,048	Y	$5,015,003	0.3893
386	380	7	12	3	2	1468.6	2.031	92.6%	$54,368	$4,948,785	$49,181	-$27,649	$12,600	-$5,819	Y	$5,003,153	0.3893
387	381	10	12	1	1	1392.1	2.016	92.6%	$45,536	$4,964,721	$42,920	-$34,630	$14,100	-$6,062	Y	$5,010,257	0.3891
388	382	7	12	1	1	1474.6	2.045	92.6%	$45,474	$4,971,899	$42,920	-$34,589	$14,100	-$5,851	Y	$5,017,372	0.3886
389	383	7	12	2	2	1528.7	2.240	93.0%	$50,093	$4,975,773	$42,600	-$38,222	$11,100	-$5,837	Y	$5,025,866	0.3884
390	384	13	12	3	1	1262.5	1.696	92.3%	$60,762	$4,954,844	$47,864	-$26,740	$15,600	-$7,437	Y	$5,015,606	0.3881
391	385	10	12	3	1	1371.4	2.005	92.3%	$55,162	$4,964,519	$48,774	-$25,227	$15,600	-$6,054	Y	$5,019,681	0.3876

Database | Analysis

Ready 95%

	A	B	C	D	E	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO
1									Sensitivity analysis variables								
2									0%	0%	0%		0%	0%	# of successful designs		407
3	All cases analysis (baseline)					Constraints										MinWorth	Best Value
4						1600.0	2.7	85%	10000000	10000000	10000000	1000000	10000000	1000000		$1,939,384	0.9920
5		Technology Number				Mass	Length	Effeciency	System Unit	Development	20 yr Ops	20 yr Ops	20 yr Maint.	Recycling/	Successful		
6	Run #	Rotor	Motor/Gen	Bearings	Vac.	(kg)	(m)	(%)	cost ($)	cost ($)	cost ($)	cost+eff.	cost ($)	disposal cost ($)	design? (Y/N)	Worth ($)	Best Value
392	386	13	12	2	1	1306.5	1.853	92.6%	$57,517	$4,974,878	$42,920	-$34,682	$14,100	-$7,451	Y	$5,032,395	0.3875
393	387	10	12	2	1	1423.6	2.191	92.6%	$51,319	$4,988,242	$42,920	-$34,630	$14,100	-$6,070	Y	$5,039,560	0.3869
394	388	7	12	3	1	1451.3	2.031	92.2%	$56,296	$4,971,672	$49,502	-$24,016	$15,600	-$5,841	Y	$5,027,968	0.3868
395	389	7	12	2	1	1509.9	2.240	92.6%	$51,975	$4,998,345	$42,920	-$34,589	$14,100	-$5,861	Y	$5,050,320	0.3860
396	390	16	11	1	2	1216.7	1.509	92.2%	$74,529	$4,975,704	$46,824	-$26,137	$11,550	-$11,225	Y	$5,050,233	0.3860
397	391	16	11	3	2	1201.3	1.500	91.9%	$81,632	$4,975,542	$51,146	-$19,193	$13,050	-$11,219	Y	$5,057,174	0.3848
398	392	16	11	2	2	1240.8	1.637	92.2%	$78,824	$4,993,267	$46,824	-$26,137	$11,550	-$11,231	Y	$5,072,091	0.3843
399	393	16	11	1	1	1202.8	1.509	91.8%	$76,598	$4,999,377	$47,144	-$22,503	$14,550	-$11,244	Y	$5,075,975	0.3835
400	394	16	11	3	1	1187.5	1.500	91.6%	$83,705	$4,999,229	$51,466	-$15,559	$16,050	-$11,237	Y	$5,082,934	0.3824
401	395	16	11	2	1	1226.0	1.637	91.8%	$80,868	$5,016,747	$47,144	-$22,503	$14,550	-$11,249	Y	$5,097,614	0.3819
402	396	16	10	1	2	1319.0	1.509	92.5%	$75,437	$5,057,208	$42,845	-$33,006	$11,250	-$11,465	Y	$5,132,645	0.3803
403	397	16	10	3	2	1303.6	1.500	92.2%	$82,540	$5,057,046	$47,167	-$26,062	$12,750	-$11,459	Y	$5,139,585	0.3792
404	398	16	10	2	2	1343.1	1.637	92.5%	$79,732	$5,074,770	$42,845	-$33,006	$11,250	-$11,471	Y	$5,154,503	0.3787
405	399	16	10	1	1	1305.1	1.509	92.1%	$77,481	$5,080,881	$43,165	-$29,372	$14,250	-$11,486	Y	$5,158,361	0.3779
406	400	16	10	3	1	1289.8	1.500	91.9%	$84,588	$5,080,732	$47,488	-$22,428	$15,750	-$11,479	Y	$5,165,320	0.3768
407	401	16	10	2	1	1328.3	1.637	92.1%	$81,750	$5,098,250	$43,165	-$29,372	$14,250	-$11,492	Y	$5,180,000	0.3763
408	402	16	12	1	2	1217.8	1.509	93.0%	$74,625	$5,455,830	$42,600	-$38,350	$11,850	-$11,254	Y	$5,530,456	0.3531
409	403	16	12	3	2	1202.4	1.500	92.7%	$81,728	$5,455,669	$46,922	-$31,406	$13,350	-$11,248	Y	$5,537,396	0.3521
410	404	16	12	2	2	1241.9	1.637	93.0%	$78,920	$5,473,393	$42,600	-$38,350	$11,850	-$11,259	Y	$5,552,314	0.3517
411	405	16	12	1	1	1203.9	1.509	92.6%	$76,694	$5,479,503	$42,920	-$34,717	$14,850	-$11,272	Y	$5,556,197	0.3510
412	406	16	12	3	1	1188.6	1.500	92.4%	$83,801	$5,479,355	$47,243	-$27,773	$16,350	-$11,266	Y	$5,563,156	0.3500
413	407	16	12	2	1	1227.1	1.637	92.6%	$80,963	$5,496,873	$42,920	-$34,717	$14,850	-$11,276	Y	$5,577,836	0.3496
414	408	11	5	2	1	1604.2	2.174	86.8%	$66,193	$1,933,124	$41,744	$22,313	$8,400	-$8,391	N	N/A	N/A
415	409	11	6	2	1	1605.3	2.174	87.6%	$66,288	$2,350,588	$37,520	$10,100	$8,700	-$8,419	N	N/A	N/A
416	410	9	5	1	1	1602.6	2.368	86.8%	$44,896	$2,732,613	$41,744	$22,325	$10,650	-$5,589	N	N/A	N/A
417	411	12	4	2	1	1603.3	2.159	87.1%	$57,828	$2,825,848	$37,765	$15,359	$10,350	-$7,456	N	N/A	N/A
418	412	9	6	1	1	1603.7	2.368	87.6%	$44,992	$3,150,077	$37,520	$10,111	$10,950	-$5,618	N	N/A	N/A
419	413	9	8	2	1	1620.7	2.572	88.8%	$53,230	$3,270,186	$45,344	$5,899	$11,250	-$5,970	N	N/A	N/A
420	414	9	9	2	1	1621.8	2.572	89.6%	$53,326	$3,714,288	$41,120	-$6,315	$11,550	-$5,998	N	N/A	N/A
421	415	7	10	2	1	1611.1	2.240	92.1%	$52,762	$4,599,722	$43,165	-$29,244	$13,500	-$6,038	N	N/A	N/A
422	416	1	1	1	1	7323.8	5.782	82.8%	$131,953	$3,097,457	$34,165	$54,599	$12,000	-$6,852	N	N/A	N/A
423	417	1	1	1	2	7365.8	5.782	83.2%	$132,037	$3,080,216	$33,845	$50,965	$9,000	-$6,735	N	N/A	N/A
424	418	1	1	2	1	7617.2	7.407	82.8%	$185,917	$3,316,977	$34,165	$54,599	$12,000	-$6,923	N	N/A	N/A
425	419	1	1	2	2	7670.0	7.407	83.2%	$186,320	$3,302,181	$33,845	$50,965	$9,000	-$6,803	N	N/A	N/A
426	420	1	1	3	1	7130.3	5.672	79.5%	$221,783	$3,095,578	$88,794	$142,360	$13,500	-$6,772	N	N/A	N/A

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	A	B	C	D	E	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO
1									Sensitivity analysis variables								
2									0%	0%	0%		0%	0%	# of successful designs		407
3	**All cases analysis (baseline)**					Constraints										MinWorth	Best Value
4						1600.0	2.7	85%	10000000	10000000	10000000	1000000	10000000	1000000		$1,939,384	0.9920
5		Technology Number				Mass	Length	Effeciency	System Unit	Development	20 yr Ops	20 yr Ops	20 yr Maint.	Recycling/	Successful		
6	Run #	Rotor	Motor/Gen	Bearings	Vac.	(kg)	(m)	(%)	cost ($)	cost ($)	cost ($)	cost+eff.	cost ($)	disposal cost ($)	design? (Y/N)	Worth ($)	Best Value
1124	1118	15	1	1	2	1569.0	1.743	83.5%	$70,828	$2,806,889	$33,845	$48,110	$7,500	-$10,897	N	N/A	N/A
1125	1119	15	1	2	1	1576.6	1.871	83.1%	$77,023	$2,847,493	$34,165	$51,744	$10,500	-$10,926	N	N/A	N/A
1126	1120	15	1	2	2	1592.9	1.871	83.5%	$75,101	$2,824,365	$33,845	$48,110	$7,500	-$10,902	N	N/A	N/A
1127	1121	15	1	3	1	1538.3	1.734	82.9%	$79,847	$2,830,062	$38,466	$58,653	$12,000	-$10,915	N	N/A	N/A
1128	1122	15	1	3	2	1553.7	1.734	83.2%	$77,895	$2,806,728	$38,146	$55,020	$9,000	-$10,891	N	N/A	N/A
1129	1123	15	2	1	1	1340.1	1.743	82.8%	$69,847	$2,717,806	$38,144	$58,612	$10,800	-$10,091	N	N/A	N/A
1130	1124	15	2	1	2	1355.6	1.743	83.2%	$67,847	$2,694,486	$37,824	$54,979	$7,800	-$10,070	N	N/A	N/A
1131	1125	15	2	2	1	1363.2	1.871	82.8%	$74,095	$2,735,090	$38,144	$58,612	$10,800	-$10,096	N	N/A	N/A
1132	1126	15	2	2	2	1379.5	1.871	83.2%	$72,121	$2,711,962	$37,824	$54,979	$7,800	-$10,076	N	N/A	N/A
1133	1127	15	2	3	1	1324.9	1.734	82.6%	$76,919	$2,717,658	$42,445	$65,522	$12,300	-$10,085	N	N/A	N/A
1134	1128	15	2	3	2	1340.3	1.734	82.9%	$74,915	$2,694,325	$42,125	$61,888	$9,300	-$10,064	N	N/A	N/A
1135	1129	15	3	1	2	1341.2	1.743	83.6%	$69,942	$3,119,368	$33,920	$46,399	$11,100	-$10,119	N	N/A	N/A
1136	1130	15	3	1	2	1356.7	1.743	84.0%	$67,943	$3,096,047	$33,600	$42,765	$8,100	-$10,099	N	N/A	N/A
1137	1131	15	3	2	1	1364.3	1.871	83.6%	$74,191	$3,136,651	$33,920	$46,399	$11,100	-$10,125	N	N/A	N/A
1138	1132	15	3	2	2	1380.6	1.871	84.0%	$72,217	$3,113,523	$33,600	$42,765	$8,100	-$10,104	N	N/A	N/A
1139	1133	15	3	3	1	1326.0	1.734	83.4%	$77,015	$3,119,220	$38,221	$53,309	$12,600	-$10,113	N	N/A	N/A
1140	1134	15	3	3	2	1341.4	1.734	83.7%	$75,011	$3,095,886	$37,901	$49,675	$9,600	-$10,093	N	N/A	N/A
1141	1135	16	1	1	1	1548.0	1.504	83.1%	$75,978	$3,560,855	$34,165	$51,745	$12,750	-$10,980	N	N/A	N/A
1142	1136	16	1	1	2	1561.9	1.504	83.5%	$73,994	$3,537,175	$33,845	$48,111	$9,750	-$10,956	N	N/A	N/A
1143	1137	16	1	2	1	1571.3	1.632	83.1%	$80,248	$3,578,225	$34,165	$51,745	$12,750	-$10,985	N	N/A	N/A
1144	1138	16	1	2	2	1586.0	1.632	83.5%	$78,289	$3,554,738	$33,845	$48,111	$9,750	-$10,961	N	N/A	N/A
1145	1139	16	1	3	1	1532.7	1.495	82.9%	$83,086	$3,560,707	$38,488	$58,689	$14,250	-$10,974	N	N/A	N/A
1146	1140	16	1	3	2	1546.6	1.495	83.2%	$81,096	$3,537,013	$38,167	$55,055	$11,250	-$10,950	N	N/A	N/A
1147	1141	16	2	1	1	1334.6	1.504	82.8%	$73,050	$3,448,452	$38,144	$58,614	$13,050	-$10,150	N	N/A	N/A
1148	1142	16	2	1	2	1348.5	1.504	83.2%	$71,013	$3,424,771	$37,824	$54,980	$10,050	-$10,129	N	N/A	N/A
1149	1143	16	2	2	1	1357.9	1.632	82.8%	$77,320	$3,465,821	$38,144	$58,614	$13,050	-$10,155	N	N/A	N/A
1150	1144	16	2	2	2	1372.6	1.632	83.2%	$75,308	$3,442,334	$37,824	$54,980	$10,050	-$10,135	N	N/A	N/A
1151	1145	16	2	3	1	1319.3	1.495	82.6%	$80,158	$3,448,303	$42,466	$65,558	$14,550	-$10,144	N	N/A	N/A
1152	1146	16	2	3	2	1333.2	1.495	82.9%	$78,116	$3,424,610	$42,146	$61,924	$11,550	-$10,123	N	N/A	N/A
1153	1147	16	3	1	2	1335.7	1.504	83.6%	$73,146	$3,850,013	$33,920	$46,400	$13,350	-$10,178	N	N/A	N/A
1154	1148	16	3	1	2	1349.6	1.504	84.0%	$71,109	$3,826,333	$33,600	$42,767	$10,350	-$10,158	N	N/A	N/A
1155	1149	16	3	2	1	1359.0	1.632	83.6%	$77,416	$3,867,382	$33,920	$46,400	$13,350	-$10,184	N	N/A	N/A
1156	1150	16	3	2	2	1373.7	1.632	84.0%	$75,405	$3,843,895	$33,600	$42,767	$10,350	-$10,163	N	N/A	N/A
1157	1151	16	3	3	1	1320.4	1.495	83.4%	$80,254	$3,849,864	$38,243	$53,344	$14,850	-$10,172	N	N/A	N/A
1158	1152	16	3	3	2	1334.3	1.495	83.7%	$78,212	$3,826,171	$37,922	$49,711	$11,850	-$10,152	N	N/A	N/A

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Vita

James Brill Clegern was born in Enid, OK, to the parents of Robert and Carol Clegern. He is the first of three children, with a brother, David, and sister, Judith. He attended High School at Sherwood High School, Maryland. After graduation in 1987, he attended the University of Maryland, College Park, where he completed his Bachelors of Science degree in Aerospace Engineering in December 1991. He also completed his Air Force Reserve Officer Training Corps program and was commissioned into the United States Air Force (USAF) as an acquisitions/engineering officer. He accepted a delay to active duty in 1992 and attended the University of Tennessee Space Institute, Tullahoma TN in their Aerospace Engineering program. James graduated with a Masters of Science degree in Aerospace Engineering in May 1993.

From May 1993 to May 2013, James served on active duty in the USAF, completing tours in Dayton, OH, Colorado Springs, CO, Lancaster, CA, Bellevue, NE and Albuquerque, NM as an Developmental Engineer, Staff Engineer, Test Director, Developmental Test Engineer, Chief Engineer, and Group Test Director. While serving at Kirtland AFB, NM in 2009, he reenrolled with the University of Tennessee Distance Learning program in the Industrial Engineering program. He is continuing his education with a Doctorate of Philosophy in Industrial Engineering at the University of Tennessee, Knoxville, TN.