An Engineering Systems Approach to Production Planning of Optical Systems

by

Henry A. Hui

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Author . . . .
System Design and Management Program
April 10, 2021

Certified by . . . .
Olivier L. de Weck
Professor of Aeronautics and Astronautics and Engineering Systems
Thesis Supervisor

Accepted by . . . .
Joan S. Rubin
Executive Director, MIT System Design and Management Program

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Abstract

Production enterprises are continuously presented with investment opportunities to improve their production systems through the adoption of new technologies. When presented with these opportunities, enterprise leaders are faced with decisions that can have profound viability implications. A value-centric framework to holistically and systematically inform and support decisions is needed.

This research introduces such a strategic framework based on Engineering Systems principles and methods. Within this framework, Enterprise System Architecting and Technology Roadmapping methods have been adapted for production systems to identify stakeholder value, create investment scenarios as project portfolios, assess performance using Discrete Event Simulation (DES) and technical modeling, and visualize options using tradespace plots.

A case study, involving a representation of the National Ignition Facility's (NIF) Optics Recycle Loop production system, is explored to demonstrate the framework process steps as a guide for its application. Each of the process steps is applied to the optics production enterprise resulting in a recommended project portfolio spanning 20 years. The baseline DES simulation predicts a throughput of 129 optics/month. After investments into debottlenecking, this was boosted to 261 optics/month. In addition, product performance forecasting predicts that after product improvement investments, optics damage threshold - a key product performance figure of merit - will improve by 67%. By using the new strategic framework, production enterprises can make decisions based on projected present and future value.

Thesis Supervisor: Olivier L. de Weck
Title: Professor of Aeronautics and Astronautics and Engineering Systems

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Acronyms

AHP Analytical Hierarchy Process

AMP Advanced Mitigation Process

AR Anti-Reflective

ARIES Architecting Innovative Enterprise Strategy

ATRA Advanced Technology Roadmap Architecture

CEA French Alternative Energies and Atomic Energy Commission

DDS Disposable Debris Shields

DES Discrete Event Simulation

DSMs Design Structure Matrices

FOA Final Optics Assemblies

FOM Figure of Merit

FSDS Fused Silica Debris Shield

GDS Grating Debris Shield

ICF Inertial Confinement Fusion

IOM Integrated Optics Module

IoT Internet of Things

ISBE Input Surface Bulk Eruptions

LLNL Lawrence Livermore National Laboratory

LMJ Laser Megajoule

LRUs Line Replaceable Units

MAU Multi-attribute Utility

MDO Multidisciplinary Design Optimization

NIF National Ignition Facility

OFAT One-Factor-At-a-Time

OMF Optics Mitigation Facility

OPD Object-Process-Diagram

OPF Optics Production Facility

OPM Object Process Methodology

ORL Optic Recycle Loop

TPR Technology Planning and Roadmapping process

WFL Wedged Focus Lens

Chapter 1

Introduction

1.1 Motivation

As new technologies advance and provide opportunities for improvement, production enterprises across multiple industries are challenged to make the right adoption decisions. Making the right decisions can lead to competitive advantages, propelling the enterprise through years of profitable growth. Conversely, making the wrong decisions can lead to disadvantages and ultimately an unsustainable enterprise. As the world embarks on what economists believe to be the Fourth Industrial Revolution [23], a number of technologies may be available to profoundly improve production systems including, but not limited to:

- Additive manufacturing
- Advanced robotics
- Machine learning
- Artificial intelligence
- Big data
- Internet of Things (IoT)

Ultimately, production enterprise leaders would like to make the best system upgrade decisions for their organizations but need a practical, systematic, value-centric approach to exploring architectural upgrade options and methods to determine which upgrades to make and when.

Production systems – manufacturing plants, processing facilities, assembly lines, etc. - vary across industries, but typically produce a product after completing a number of processes that may or may not require human interaction. In addition to technology infusion, these systems also typically evolve over time due to aging infrastructure, competition, market demands, and changing industry landscapes. As with any company in any industry, production enterprises need to continuously evaluate their vulnerabilities to disruption and act accordingly. Economist Klaus Schwab suggests that all industries and companies must consider the question "When is disruption coming, what form will it take and how will it affect me and my organization?" [23].

To help answer that question and to make better-informed decisions, we can look to new areas of Engineering Systems research in Enterprise Systems Architecting, and Technology Roadmapping. Enterprise Systems Architecting is an intriguing area of study focusing on the transformation of enterprises for optimal alignment to industry needs. Technology Roadmapping methods may be most applicable as it focuses on technological advancement, and project portfolio selection. A survey conducted by Schimpf and Abele (figure 1-1) suggests that while Technology Roadmapping is indeed applied to production planning in industrial companies, it is applied much less frequently when compared to other application areas. Both of these Engineering Systems research areas offer promising methods and if adapted and combined, may provide the production system evolution planning framework we are seeking.

1.2 Thesis Objectives and Approach

The purpose of this research is to prescribe a practical framework that can be used by production system enterprises to strategically plan for phased system upgrades

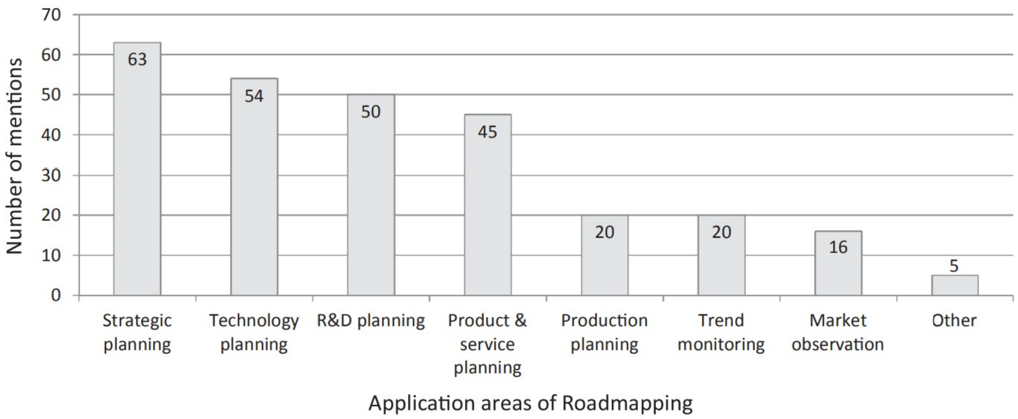


Figure 1-1: Frequency of application areas for roadmapping in industrial companies in Germany [22]

by considering multiple architectural options within a project portfolio design space evaluated by multiple objectives. Engineering Systems methods in general focus on delivering value by properly defining the problem space, and strategically navigating the solution space to maximize value. In theory, Engineering Systems methods can be applied to any system, including production systems where potential upgrade projects within a portfolio represent the design space.

As more organizations adopt Engineering Systems methods as a form of risk mitigation for projects, can similar techniques be used to improve decision-making for production systems? Enterprise System Architecting case studies tend to focus on systems at the company level [18]. Can Enterprise Systems Architecting methods be used effectively to envision future landscapes and future stakeholder needs for production systems that are often part of larger organizations? Technology Roadmapping relies heavily on quantitative technical models to forecast performance. Are there practical modeling methods that can be used for production systems? Can Technology Roadmapping methods be used to scout and assess technology and its usefulness to the production system?

A literature review was conducted to understand methods proposed by researchers for strategic decision-making specifically for production system enterprises. The review uncovered proposed methods involving the Analytical Hierarchy Process (AHP), and cost-centric, multi-objective optimization methods. The review also explored two new research areas within Engineering Systems that focus on aligning enterprises to industry needs.

A case study, drawn from industry, was developed to demonstrate a new proposed framework adapted from methods introduced by Engineering Systems researchers O. de Weck, D. Nightingale, and D. Rhodes. It navigates the full 8-step process outlined in Chapter 3 to showcase its effectiveness in understanding present and future value, generating investment scenarios, practical system modeling, linking scenarios to stakeholder value, and ultimately, the recommendation of a set of projects within a project portfolio.

1.3 Key Research Questions

The key questions the research seeks to address to build a framework are:

- How can production system enterprises forecast future external landscapes and future stakeholder needs to strategically plan system architecture upgrades over time to maximize value?
- How do you identify key figures of merit (FOMs) to properly assess and track technology development?
- How do enterprises scout and assess technology and its usefulness to a production system?

1.4 Thesis Structure

This thesis is organized into the five chapters outlined in figure 1-2. The thesis flow begins with introduction and literature review chapters. A new proposed framework is introduced in chapter 3 followed by a case study in chapter 4 to demonstrate the framework using a real-world production system. Chapter 5 concludes the thesis with a summary of findings and recommendations.

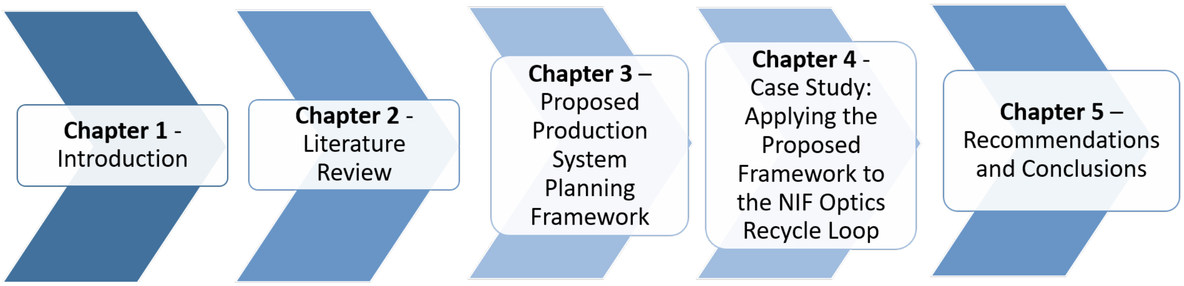


Figure 1-2: Schematic depicting the flow and logic of the five thesis chapters

Chapter 1 - Introduction: This chapter summarizes the motivation for the research and underscores the importance of decision-making methods for production system planning within any industry. It defines the research objectives, the approach and key questions to be addressed by the research.

Chapter 2 - Literature Review: This chapter summarizes prior research in production system decision-making methods and Engineering Systems decision-making methods and identifies where other research can be leveraged and adapted to achieve the thesis objective.

Chapter 3 - Proposed Production System Planning Framework: This chapter introduces a new framework adapted from other research. It outlines a step-by-step decision-making process for the strategic planning of production systems based on Engineering Systems principles, methods, and tools.

Chapter 4 - Case Study: Applying the Proposed Framework to the NIF Optics Recycle Loop: This chapter demonstrates the effectiveness and practicality of the proposed framework using a representation of the National Ignition Facility's Optics Recycle Loop production system.

Chapter 5 - Recommendations and Conclusions: This chapter summarizes the research objectives and findings. It outlines recommendations for future work to build upon this framework.

Appendix: The appendix includes additional tables excluded from the main sections.

Chapter 2

Literature Review

2.1 Decision-making Methods for Production Systems

The research indicates that while there have been studies on decision-making methods for manufacturing and processing systems, few researchers have taken a value-based, systems engineering approach to developing a practical method that considers product performance and throughput benefits of investments, and their alignment to future enterprise needs. Two decision-making methods specifically for production systems were found:

- AHP (Analytical Hierarchy Process)
- Industrial Cost Modeling

Both methods explore architectural changes to the system and performance implications based on a set of objectives. The following sections describe the two methods in greater detail and explore their limitations.

2.1.1 Analytical Hierarchy Process

The Analytical Hierarchy Process is a well-established decision-making approach widely used across various industries. It was developed by Thomas L. Saaty as a multi-criteria approach where decision-making factors are arranged in a hierarchic structure [21]. Criteria and subcriteria are ranked and weighted through pairwise comparisons. Alternatives – decision choices - are then scored with respect to each criterion and subcriterion again through pairwise comparisons. Figure 2-1 is a sample AHP hierarchy by Saaty showing the goal at the top level, criteria at the middle level, and the alternatives at the bottom level [21].

Oeltjenbruns et al. then investigated its compatibility with strategic planning specifically for a machine replacement case at Deutsche Aerospace Airbus in Germany [19]. Oeltjenbruns et al. outlined a series of steps for the AHP process adapted for manufacturing systems [19]:

1. ***Specification of investment alternatives and evaluation criteria*** – This step calls for the development of feasible investment alternatives first, followed by criteria for evaluation.

2. ***Pairwise comparison of criteria and categories*** – All criteria (categories here are simply grouped criteria in this method) are evaluated for importance using managerial judgments where criteria are compared to each other in pairs and assigned numerical values from 1-9 (introduced by Saaty in the fundamental scale shown in table 2.1) depending on the relative importance of one versus the other. The numerical values are entered into an n x n square matrix where n(n-1)/2 judgments (and their assigned numerical values) are generated along with the same number of reciprocals derived [21]. Table 2.2 is an example of the mathematical operations [19].

3. ***Rating of investment alternatives*** – Each investment alternative is to be rated with respect to every criterion. Oeltjenbruns et al. suggest that qualitative (intangible) criteria ratings can be attained through pairwise comparisons while quantitative criteria can be rated using existing or estimated performance data.

4. ***Investment rankings*** – The final step involves combining all the alternative

ratings into a single overall rating where the alternative with the highest overall ranking is considered the best choice.

The process was applied to a real-world case study where several investment alternatives for the partial upgrade or replacement of milling machines at a Deutsche Aerospace Airbus plant required decision analysis. This case study considered a total of 6 different investment alternatives for 2 total machines. The criteria included financial (manufacturing and investment costs), technological (machine performance), and intangible (non-functional "ilities") considerations. Oeltjenbruns et al. concluded that ultimately, the use of AHP was beneficial to management. It allowed them to consider a greater breadth of technological and strategic criteria, engaged and motivated staff through group decision-making and allowed for a better understanding of the basis for decision making.

While AHP applied to manufacturing systems can be beneficial in providing decision-making insights, there are a number of limitations that hinder its effectiveness. Oeltjenbruns et al. reported difficulties with the following:

- Consistency in criteria evaluation for large matrices
- Hesitancy from ranking participants in providing judgments of preference
- Scoring alternatives in qualitative (intangible) criteria
- Participant confidence in pairwise comparison (subjective) of qualitative criteria as opposed to a performance-based scoring system measured against some baseline performance (meets, exceeds, etc.)

AHP may be sufficient for cases with a relatively small set of machine-specific alternatives (like the 6 considered by Oeltjenbruns et al.) but may be impractical for a larger set orders of magnitude greater that a full production system's long-term upgrade plan may require. The pairwise analysis time and effort increase exponentially with every additional alternative which may magnify the consistency issues reported by Oeltjenbruns et al.

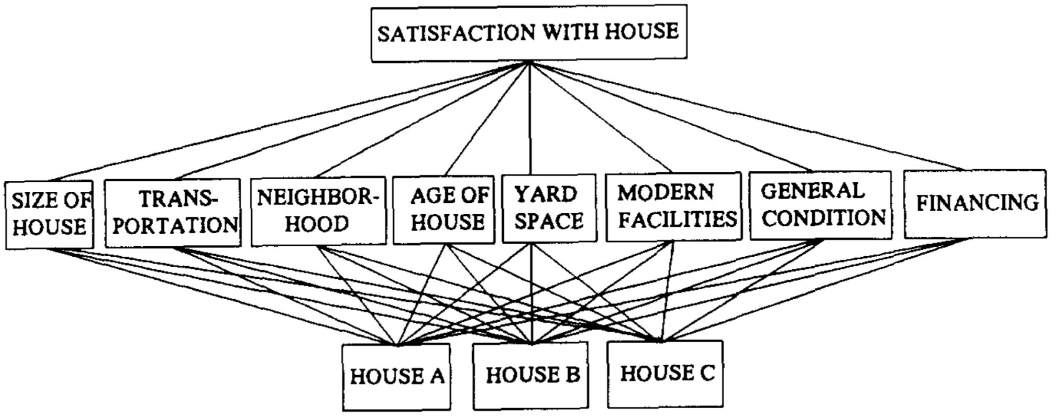


Figure 2-1: AHP decomposition of the problem [21]

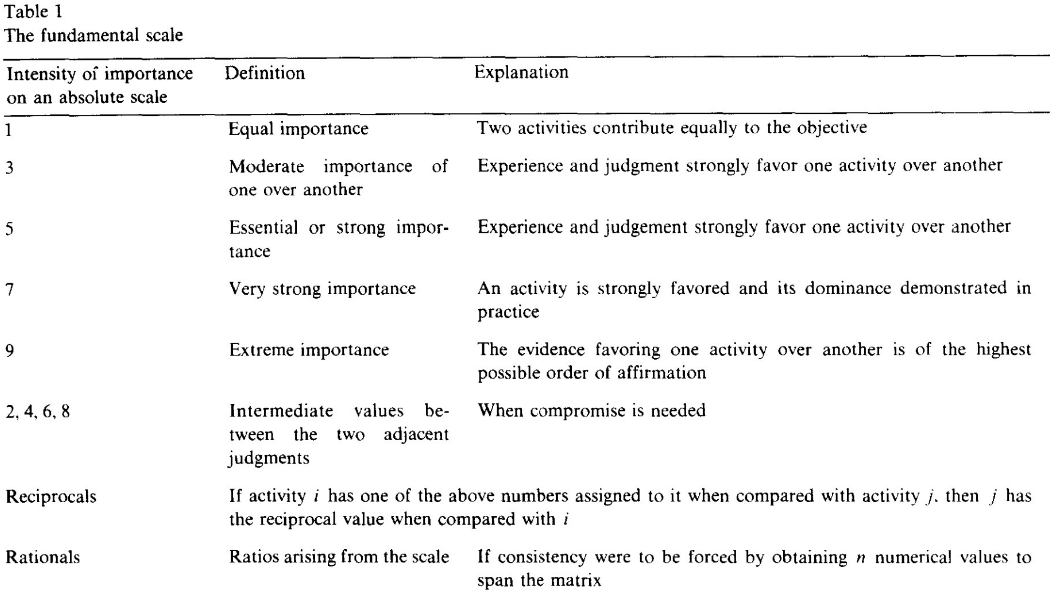
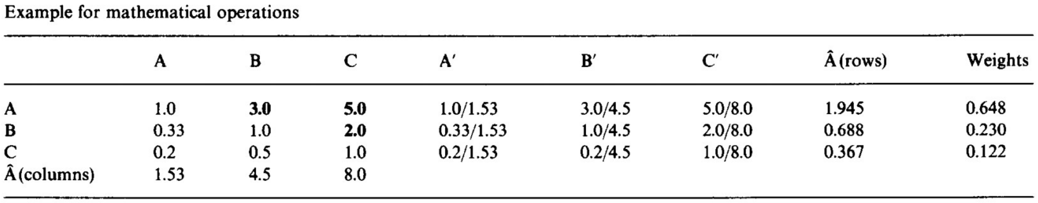


Table 1
The fundamental scale

Intensity of importance on an absolute scale	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment strongly favor one activity over another
5	Essential or strong importance	Experience and judgement strongly favor one activity over another
7	Very strong importance	An activity is strongly favored and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgments	When compromise is needed
Reciprocals	If activity *i* has one of the above numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	
Rationals	Ratios arising from the scale	If consistency were to be forced by obtaining *n* numerical values to span the matrix

Table 2.1: The fundamental scale introduced by Saaty [21]



Example for mathematical operations

	A	B	C	A′	B′	C′	Â(rows)	Weights
A	1.0	**3.0**	**5.0**	1.0/1.53	3.0/4.5	5.0/8.0	1.945	0.648
B	0.33	1.0	**2.0**	0.33/1.53	1.0/4.5	2.0/8.0	0.688	0.230
C	0.2	0.5	1.0	0.2/1.53	0.2/4.5	1.0/8.0	0.367	0.122
Â(columns)	1.53	4.5	8.0					

Table 2.2: Example of AHP mathematical operations [19]

2.1.2 Industrial Cost Modeling

Cost estimation and analysis is an essential part of the decision-making process for the strategic planning of production systems to understand the potential cost-savings as benefits, and potential costs incurred as upgrade investments. Pehrsson et al. introduce a new method for supporting economically sound decision-making in manufacturing enterprises. The focus of industrial cost modeling as described by Pehrsson et al. is the accurate and comprehensive creation of a cost model to be used alongside process simulation models such as discrete event simulation. The method systematically organizes and considers an extensive list of typical process and equipment-related costs that contribute to a production system's running cost. A large set of design alternatives (20k) are considered in a hypothetical automotive industry production line case study where an NSGA-II algorithm (non-dominated sorting genetic algorithm) is used to search for optimal solutions [20].

The industrial cost modeling process flow consists of creating a production system model, identifying optimization objects and constraints, incorporating alternatives and cost models, running the optimization, and finally, analyzing the data to extract knowledge [20]. A flow chart of the process is shown in figure 2-2. Product design options considered are translated into manufacturing design options that improve process-step-specific performance at a cost. The 20k unique scenario combinations considered in the production line case study improve the availability, process times, and production buffers at various process steps. The cost model inputs are station availability, processing times, throughput, and cost of incremental station investments. The process simulation model inputs are availability and process times. The cost model outputs include the full production system running cost, and investment cost for each scenario considered. The process simulation model outputs include throughput and the lean buffer capacity.

After running the simulation, non-dominated data-filtered solutions near the Pareto frontier are presented to allow for exploration of the tradeoffs between the multiple objectives. Figure 2-3 shows a tradespace plot of investment costs versus production throughput for the automotive industry case study conducted by Pehrsson et al.

This method introduced by Pehrsson et al. is an effective approach to accurately estimate the cost implication of system changes. While this method may be highly beneficial for some cases where running costs are paramount, it may be of less value to production system managers more focused on improving throughput and product performance than operating expenses. Moreover, this method appears to rely heavily on quantitative analysis requiring extensive cost data and estimated machine performance. Methods to incorporate qualitative analysis may be needed to cover the breadth of intangible production system constraints and objectives.

2.2 Engineering Systems Methods

2.2.1 Enterprise Systems Architecting

Enterprise Systems Architecting, according to Nightingale and Rhodes, is a "strategic approach which takes a systems perspective, viewing the entire enterprise as a holistic system encompassing multiple views such as organization view, process view, knowledge view, and enabling information technology view in an integrated framework" [17]. To sustain value to its stakeholders, enterprises continually evolve due to changing needs, desired growth, new market opportunities, and threats to existence [17]. Nightingale and Rhodes, subject matter experts in enterprise architecting, introduce a framework based on a holistic approach to creating a roadmap for enterprise transformation to sustain or improve on value delivery. The framework introduced is called the Architecting Innovative Enterprise Strategy (ARIES) framework. Its intent is to provide a systematic approach to help enterprise leaders move from new thoughts, to ideas, to tangible plans [17]. The framework consists of ten unique lenses to view and analyze enterprises, a process to determine the enterprise strategy, and techniques to apply within the process [18].

The enterprise element model hierarchically breaks down enterprise components starting with its ecosystem and decomposes down to processes, organization, and

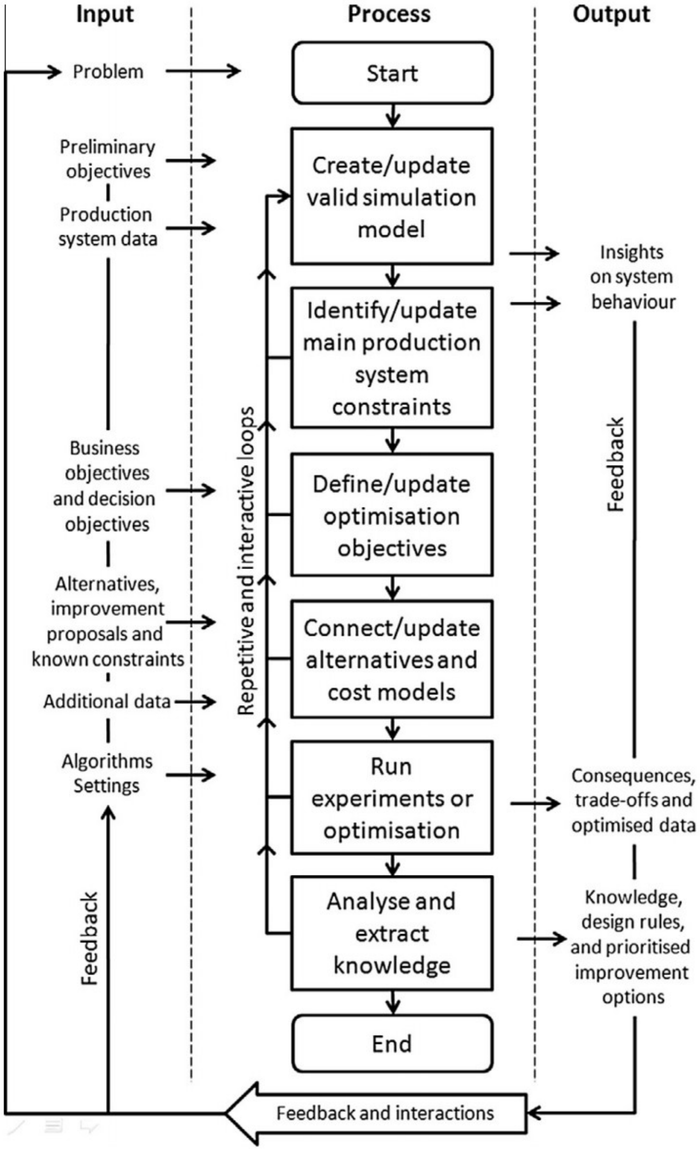


Figure 2-2: Industrial cost modeling flowchart [20]

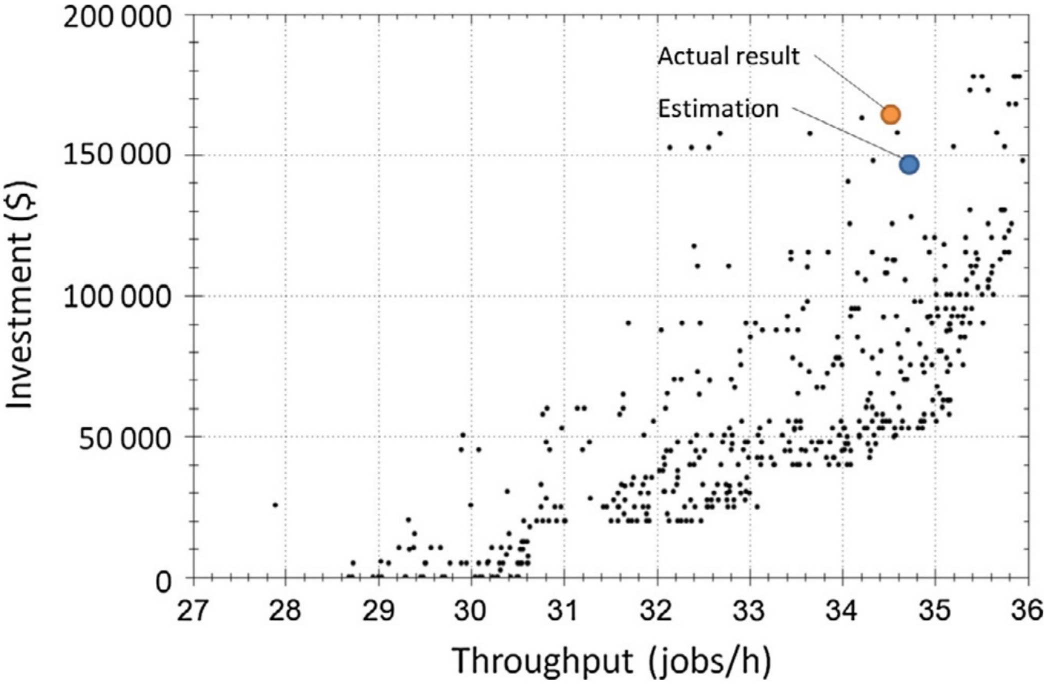


Figure 2-3: Industrial cost modeling investment v. throughput tradespace plot [20]

knowledge. This holistic view and analysis starting with the ecosystem and then stakeholders is particularly effective in aligning enterprise strategy to future industry needs to maximize value delivery. The model dives deeper into the layers of the enterprise down to the products and services produced, and then even further down to the enabling process, organization, and knowledge. Figure 2-4 outlines the layered view of the 10 lenses.

The process towards informing an enterprise transformation strategy focuses on first identifying pathways to delivering value by analyzing the landscape, stakeholders, current architecture, and envisioning the future landscape. Alternative enterprise architectures are then generated and evaluated against a set of metrics derived from key stakeholder value (derived from the envisioned future). Finally, an implementation plan is developed to transform the enterprise. Figure 2-5 depicts the process flow.

The techniques introduced allows for both qualitative and quantitative decision-making. One of the effective techniques for stakeholder analysis is the qualitative ranking of stakeholders shown in the stakeholder value map in figure 2-6. Understanding the performance of the system in delivering value to its most important stakeholders, and where improvements can be made is fundamental to unlocking a value-increasing transformation strategy. Another effective technique introduced is the DSM-based (Design Structure Matrix) X-matrix used to evaluate the current architecture for proper alignment with stakeholder values. It consists of four individual Design Structure Matrices (DSMs) that first assess the alignment between stakeholder value and the strategic objectives. The strategic objective should be well-aligned to the stakeholder values. The performance measures are then checked to ensure that they properly assess the performance of the strategic objectives and the key enterprise processes. Misaligned areas represent opportunities for architectural improvement. Figure 2-7 is a sample X-matrix for a health clinic provided by Nightingale and Rhodes where darker boxes represent stronger alignment.

Overall, the ARIES framework provides an excellent general enterprise framework for adaptation to a more production-system-specific framework. It offers the holistic views and considerations needed to ensure the production system remains sustainable. It also offers effective techniques to help organize and analyze current and future pathways to deliver stakeholder value. While decision-making techniques such as Pugh analysis are well-presented, production system enterprises likely require more advanced model-based approaches to simulate the production system prior to a more quantitative approach to decision-making such as tradespace exploration.

2.2.2 Technology Roadmapping

Technology roadmapping is the process of creating a temporal plan that links technologies and their performance to current or future products and services. It allows enterprises to forecast and manage technology evolution and supports decision making in Research and Technology (R&T) investments - budget allocations and project portfolio definition [9]. Knoll et al. describe a concurrent design approach for model-based technology roadmapping called the Technology Planning and Roadmapping process (TPR). This quantitative approach strictly relies on models for technical and financial assessment of the implementation of technology.

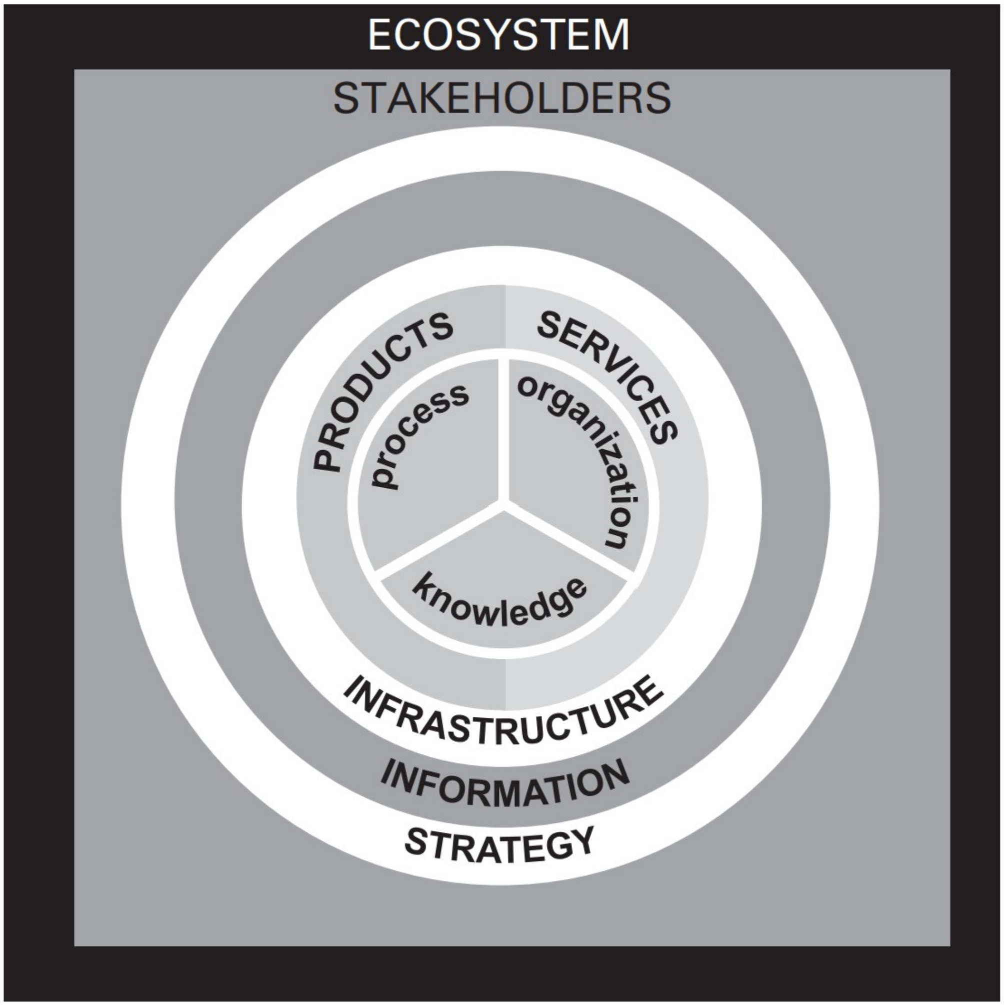


Figure 2-4: ARIES 10 unique lenses for looking at the enterprise [18]

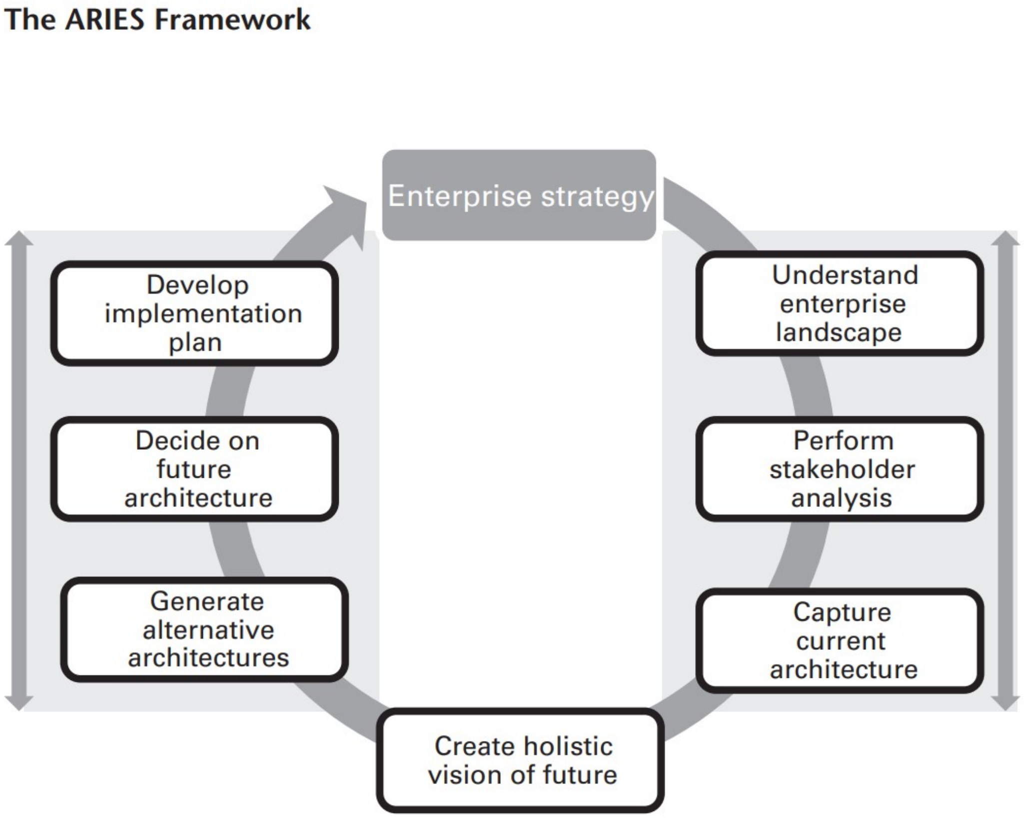


Figure 2-5: Seven activities using the applied ARIES techniques and element lenses [18]

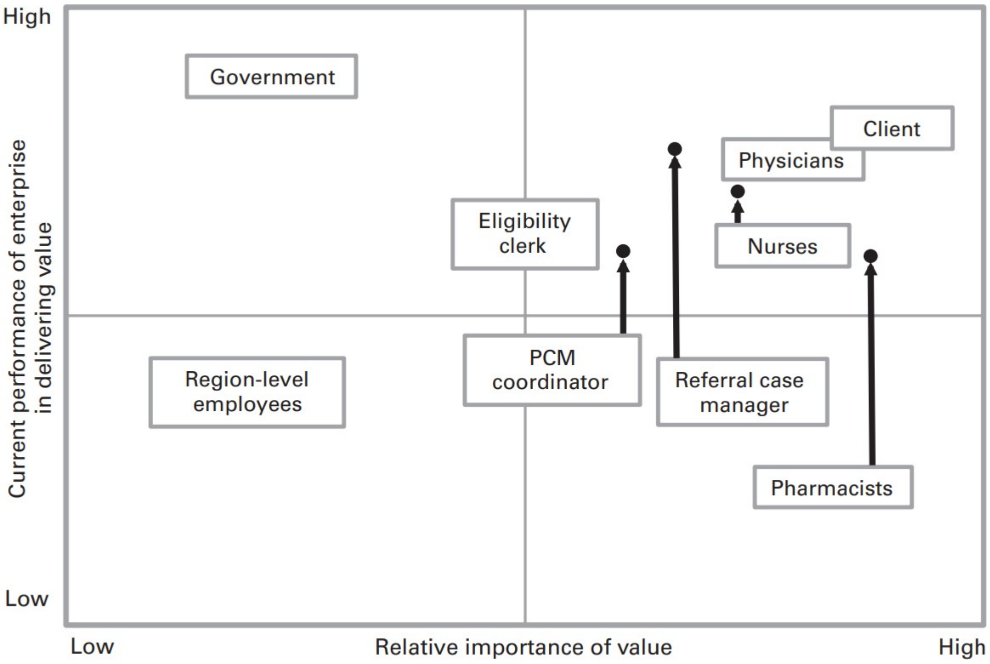
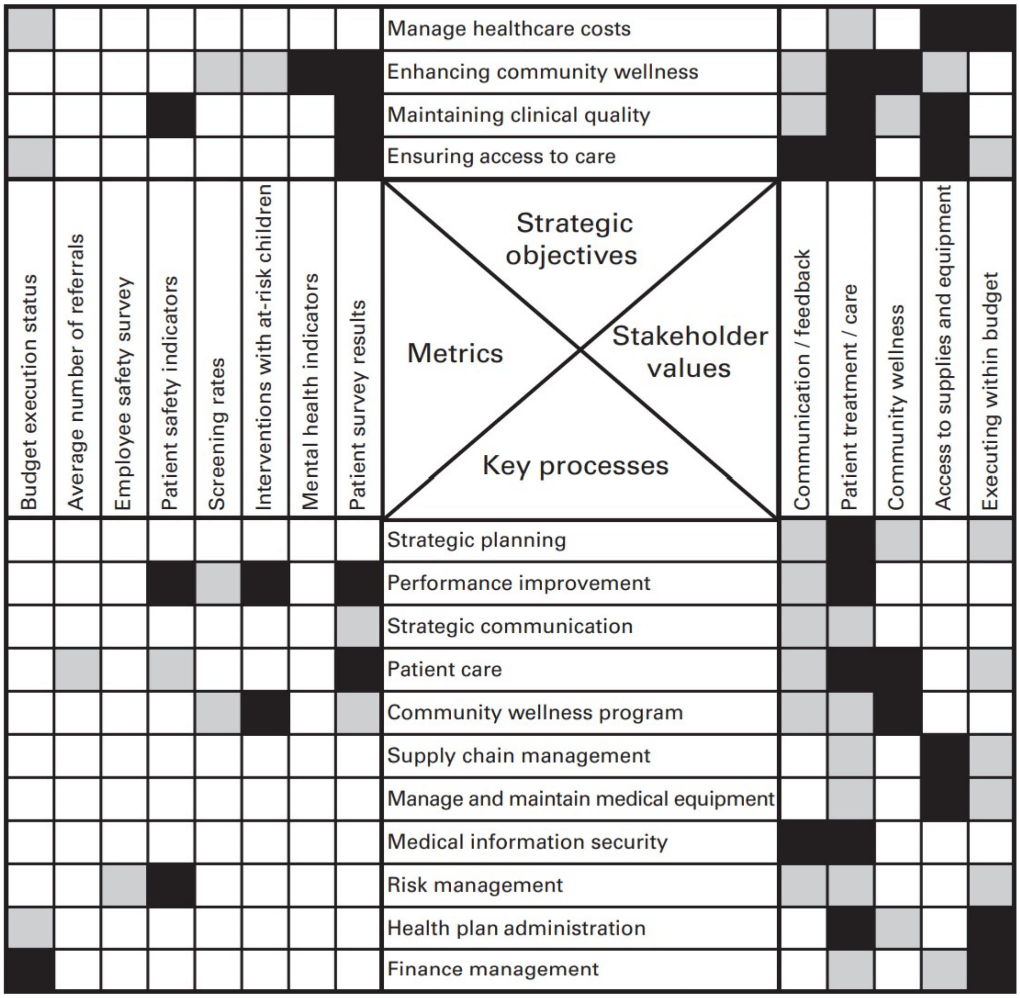


Figure 2-6: Consolidated stakeholder value exchange [18]

de Weck then further expands on the TPR approach with the introduction of the Advanced Technology Roadmap Architecture (ATRA) methodology consisting of the 4 major steps [5]:

1. Where are we today? – Technology Roadmapping and Assessment
2. Where could we go? – System Architecture Exploration (CDF)
3. Where should we go? – Scenario Analysis and Technology Valuation
4. Where we are going! – R&T Portfolio Definition & Demonstrator Plans

Figure 2-8 describes the inputs and outputs for each of the steps. The first step in the process calls for a baseline assessment of the current status in terms of market position, products, services, technology performance, and funded projects [5]. Each of the organization's products and services are examined to understand their enabling technologies. R&D projects are then examined and linked to the enabling technologies that are expected to benefit through Figure of Merit (FOM) improvements. The



	Budget execution status	Average number of referrals	Employee safety survey	Patient safety indicators	Screening rates	Interventions with at-risk children	Mental health indicators	Patient survey results	Communication / feedback	Patient treatment / care	Community wellness	Access to supplies and equipment	Executing within budget
Manage healthcare costs	▨									▨		■	■
Enhancing community wellness					▨	▨	■	■	▨	■	■	▨	
Maintaining clinical quality				■				■	▨	■	▨	■	
Ensuring access to care	▨							■	■	■		■	▨

	Budget execution status	Average number of referrals	Employee safety survey	Patient safety indicators	Screening rates	Interventions with at-risk children	Mental health indicators	Patient survey results	Communication / feedback	Patient treatment / care	Community wellness	Access to supplies and equipment	Executing within budget
Strategic planning									▨	■	▨		▨
Performance improvement				■	▨	■		■	▨	■			
Strategic communication								▨	▨	▨			
Patient care		▨		▨				■	▨	■	■		▨
Community wellness program					▨	■		▨	▨	▨	■		
Supply chain management										▨		■	▨
Manage and maintain medical equipment										▨		■	▨
Medical information security									■	■			
Risk management			▨	■					▨	▨			▨
Health plan administration	▨									■	▨		■
Finance management	■									▨		▨	■

Figure 2-7: X-matrix for a health clinic [18]

output of this step is a set of FOM tradespace charts showing the organization's current performance position compared to competitors and to the current state-of-the-art (considered the Pareto frontier). The second step explores the possible new products and services from a performance perspective to synthesize a set of architectural scenarios to consider and explore. The third step analyzes the scenarios considered using technical and financial models to rank forecasted performance against a set of specific FOM targets. Figure 2-9 describes a product-specific technical model that relies on forecasted product FOMs, and a transfer function to forecast product FOMs with and without R&T projects. The final step in the process involves building a competitive project portfolio by making decisions to start, stop, keep, or change projects based on insights gained from the roadmapping process, and the overall portfolio budget. To clearly communicate the basic details for a technology roadmap, de Weck proposes an outline consisting of the 12 elements listed in table 2.3 [5].

The technology roadmapping methods introduced by Knoll et al. and de Weck provide an excellent foundation to formulate a practical framework for project portfolio decision-making for production systems. While it is understood that validating technology roadmaps with quantitative technical and financial models lends credibility, the expertise required to create and run advanced Multidisciplinary Design Optimization (MDO), or other concurrent design methods may be cost-prohibitive for some production system organizations. More practical, user-friendly modeling techniques may serve a broader range of users.

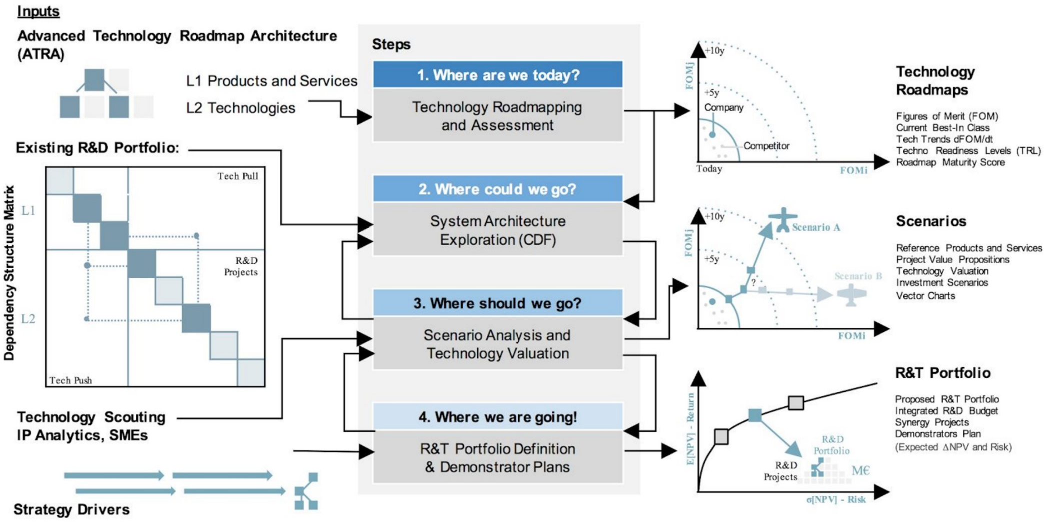


Figure 2-8: Advanced Technology Roadmap Architecture (ATRA) [5]

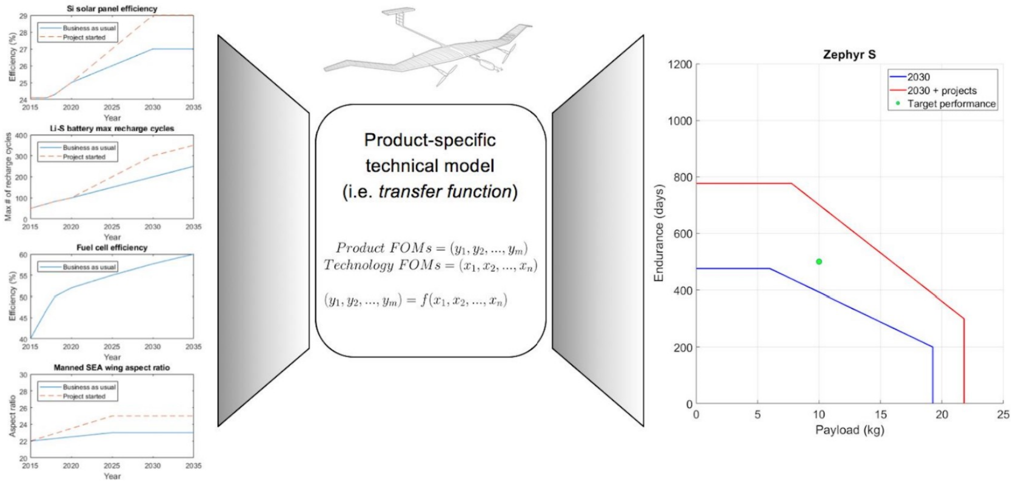
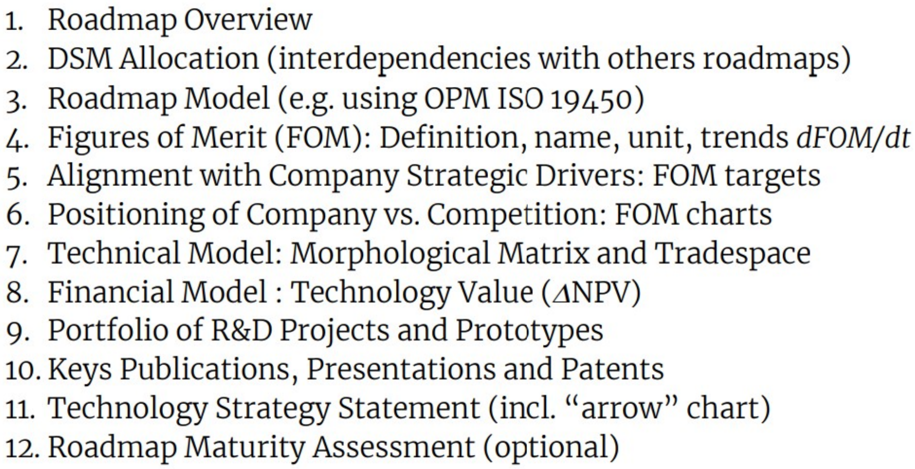


Figure 2-9: Project evaluation using a product-specific technical model [5]



1. Roadmap Overview
2. DSM Allocation (interdependencies with others roadmaps)
3. Roadmap Model (e.g. using OPM ISO 19450)
4. Figures of Merit (FOM): Definition, name, unit, trends *dFOM/dt*
5. Alignment with Company Strategic Drivers: FOM targets
6. Positioning of Company vs. Competition: FOM charts
7. Technical Model: Morphological Matrix and Tradespace
8. Financial Model : Technology Value (ΔNPV)
9. Portfolio of R&D Projects and Prototypes
10. Keys Publications, Presentations and Patents
11. Technology Strategy Statement (incl. “arrow” chart)
12. Roadmap Maturity Assessment (optional)

Table 2.3: Technology roadmap outline [5]

Chapter 3

Proposed Production System Planning Framework

An 8-step process for selecting a project portfolio to strategically upgrade production systems from a broad range of industries is described in this chapter. It combines adapted methods developed for architecting enterprise systems, and for developing technology roadmaps to provide a practical framework to align the future system architecture to future stakeholder needs. The process (outlined in figure 3-1) begins with an exploration of the production system's architecture, and research to understand industry trends and enabling technologies. After extracting key FOMs most valued by stakeholders, and identifying prospective projects, models are created to forecast throughput, product performance, and project-related costs. The process concludes with the value-based selection of projects to include in the portfolio.

3.1 Step 1: Explore Current State of the Production System

Exploration of the production system involves both a holistic view of the system within its industry through a technology roadmap dependency lens and a system-centric view through a system architecture lens. A good understanding of how the

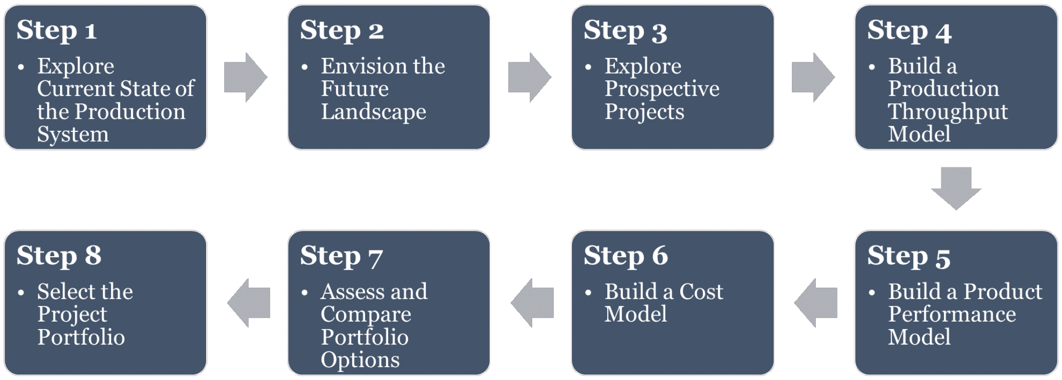
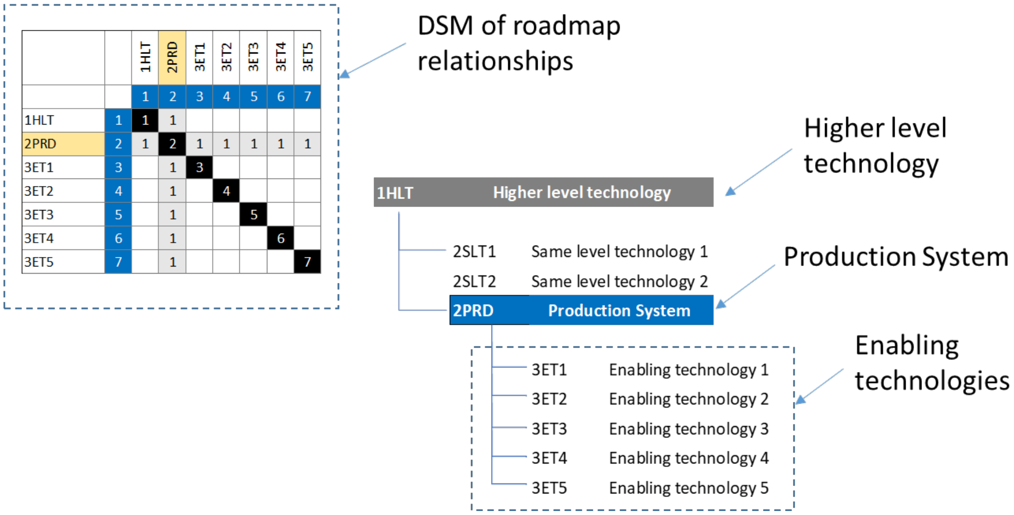


Figure 3-1: Proposed 8-step framework

technology produced by the production system enables the advancement of higher-level technologies is critical in shaping the drivers for change. Those higher-level technology roadmaps represent upstream demand and can be explored to extract market trends and future industry needs. Equally important are the production system's enabling technologies that can also be explored for potential infusion. An effective way to explore roadmap relationships is with a Design Structure Matrix (DSM), and the use of roadmap relationship tree developed by de Weck and described in figure 3-2.

Clearly identifying the system's architecture – its boundaries, accompanying systems, key subsystems, main processes, and FOMs – helps to uncover potential areas for system improvement. Creating an Object-Process-Diagram (OPD) can provide a clear view of the relationships between FOMs, processes, and objects of form. This is particularly useful later when FOM targets are identified, and form or process upgrades are needed to achieve the increases desired. The OPD also provides a good visual workspace for exploring alternate architectures using various instances of form. Figure 3-3 is an example that can be used as a guide to creating a production system OPD for architecture exploration.



		1HLT	2PRD	3ET1	3ET2	3ET3	3ET4	3ET5
		1	2	3	4	5	6	7
1HLT	1	1	1					
2PRD	2	1	2	1	1	1	1	1
3ET1	3		1	3				
3ET2	4		1		4			
3ET3	5		1			5		
3ET4	6		1				6	
3ET5	7		1					7

Figure 3-2: DSM of technology roadmap relationships. Acronyms shown are placeholders. When creating a DSM, each technology considered should be labeled first with a number representing the technology level, followed by a 2-4 letter acronym representing the products or technologies.

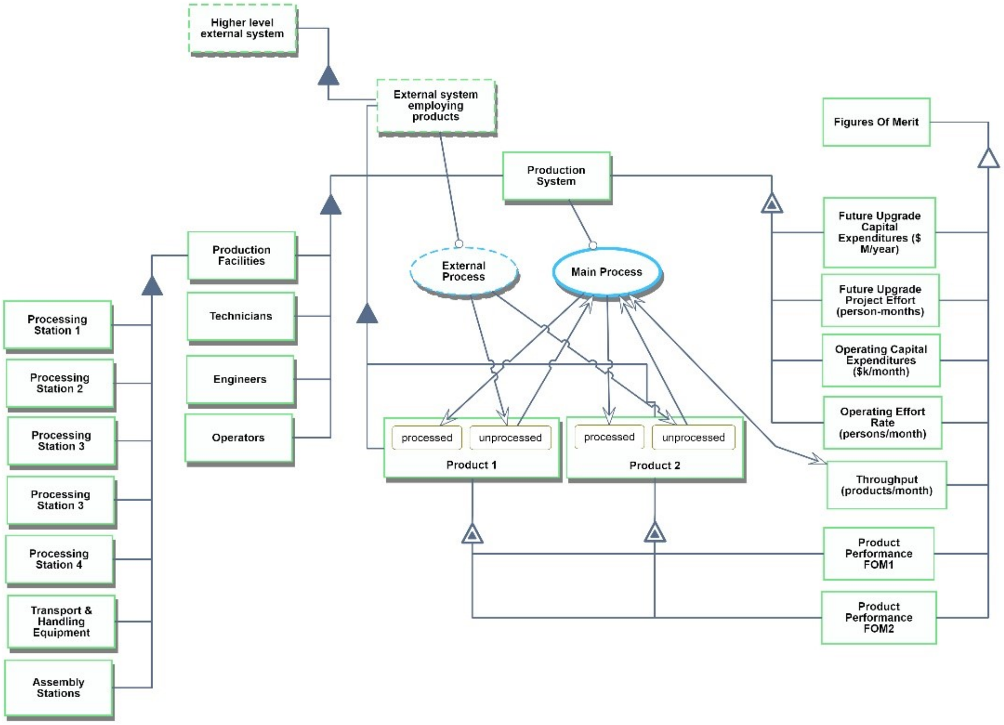


Figure 3-3: Example of an OPD highlighting FOM relationships

3.2 Step 2: Envision the Future Landscape

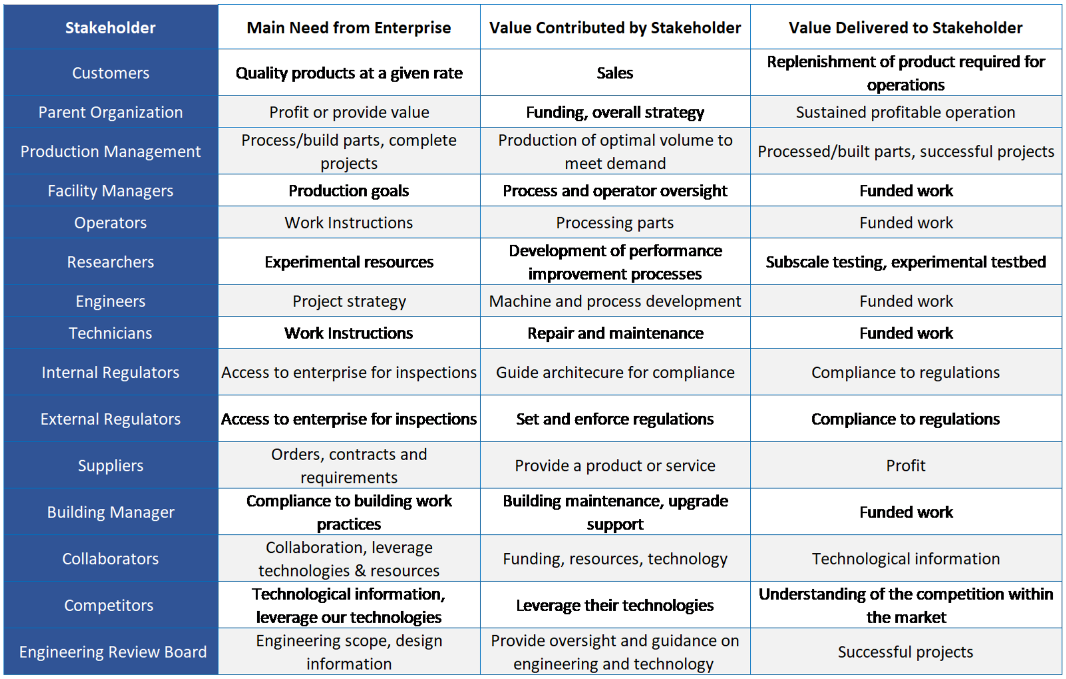
To envision the future landscape, a 3-pronged approach is used to determine the production system's strategic drivers:

1. Research industry trends to forecast the future needs of the industry
2. Identify key stakeholders and their values
3. Derive key figures of merit and strategic objects using a DSM-based X-matrix

To better align to the ever-changing landscape for the production system, research must be conducted to learn about the short-term and long-term industry goals, and general direction. Research methods include direct discussions with industry subject matter experts (customers, researchers, etc.), review of competitor product performance, and review of related technological publications, conference presentations, and patent trends. The idea here is to look beyond the present situation and envision the future landscape and its pathways to deliver value to stakeholders.

An effective way to identify stakeholders and their values is to create a stakeholder list as shown in table 3.1. Each stakeholder can then be assessed and ranked in a *Relative Importance v. Performance of the system in delivering value* plot. Figure 3-4 is an example of a plot where the system's performance in delivering value can be improved for the 3 most important stakeholders (customers, parent organization, and the production management team).

Once the most important stakeholders are identified, an X-matrix consisting of four DSMs can be used to derive the key figures of merit, and the key strategic objectives. This process starts with listing the key stakeholder values (value delivered by the system to the most important stakeholders), followed by listing potential strategic objectives, and system processes. Evaluating the strengths of relationships first in the Object-Value and the Process-Value DSMs helps to identify the key objectives and processes. Moving on to evaluating the strengths of relationships in the Object-Metric and Process-Metric DSMs considering only the key objectives, and processes then helps to identify the key FOMs. Figure 3-5 is an X-matrix example that can be



Stakeholder	Main Need from Enterprise	Value Contributed by Stakeholder	Value Delivered to Stakeholder
Customers	**Quality products at a given rate**	**Sales**	**Replenishment of product required for operations**
Parent Organization	Profit or provide value	**Funding, overall strategy**	Sustained profitable operation
Production Management	Process/build parts, complete projects	Production of optimal volume to meet demand	Processed/built parts, successful projects
Facility Managers	**Production goals**	**Process and operator oversight**	**Funded work**
Operators	Work Instructions	Processing parts	Funded work
Researchers	**Experimental resources**	**Development of performance improvement processes**	**Subscale testing, experimental testbed**
Engineers	Project strategy	Machine and process development	Funded work
Technicians	**Work Instructions**	**Repair and maintenance**	**Funded work**
Internal Regulators	Access to enterprise for inspections	Guide architecure for compliance	Compliance to regulations
External Regulators	**Access to enterprise for inspections**	**Set and enforce regulations**	**Compliance to regulations**
Suppliers	Orders, contracts and requirements	Provide a product or service	Profit
Building Manager	**Compliance to building work practices**	**Building maintenance, upgrade support**	**Funded work**
Collaborators	Collaboration, leverage technologies & resources	Funding, resources, technology	Technological information
Competitors	**Technological information, leverage our technologies**	**Leverage their technologies**	**Understanding of the competition within the market**
Engineering Review Board	Engineering scope, design information	Provide oversight and guidance on engineering and technology	Successful projects

Table 3.1: Example of a stakeholder list for a production system

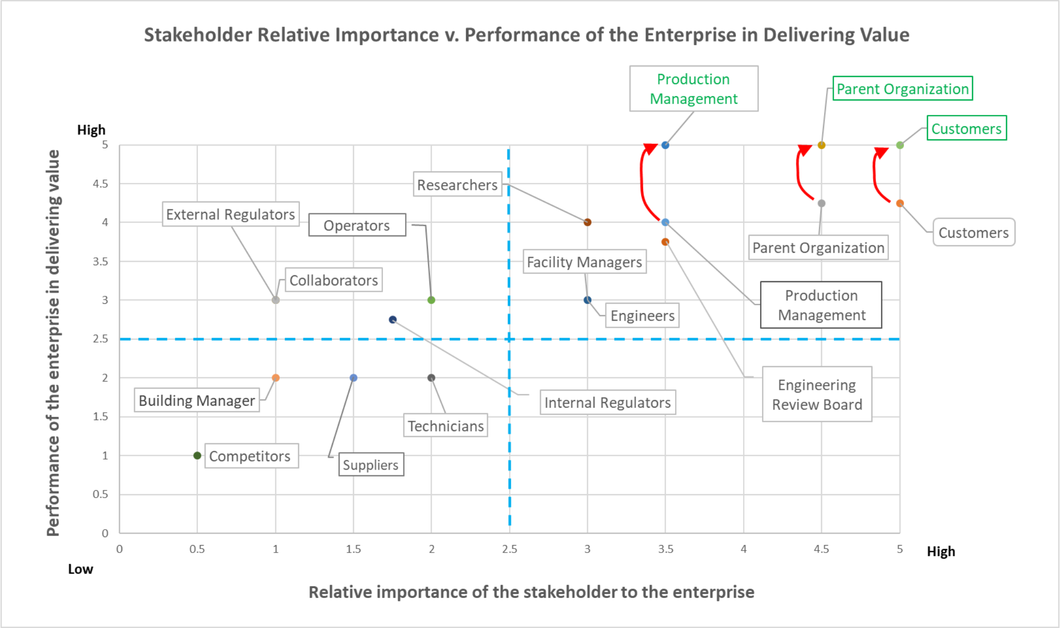


Figure 3-4: Example of a plot depicting Performance of the enterprise delivering value v. Relative importance of the stakeholder to the enterprise

used as a guide. The key strategic objectives and the key FOMs should be clearly defined. The strategic objectives should contain clear targets for FOM improvements, a means of obtaining the goals, and target completion dates.

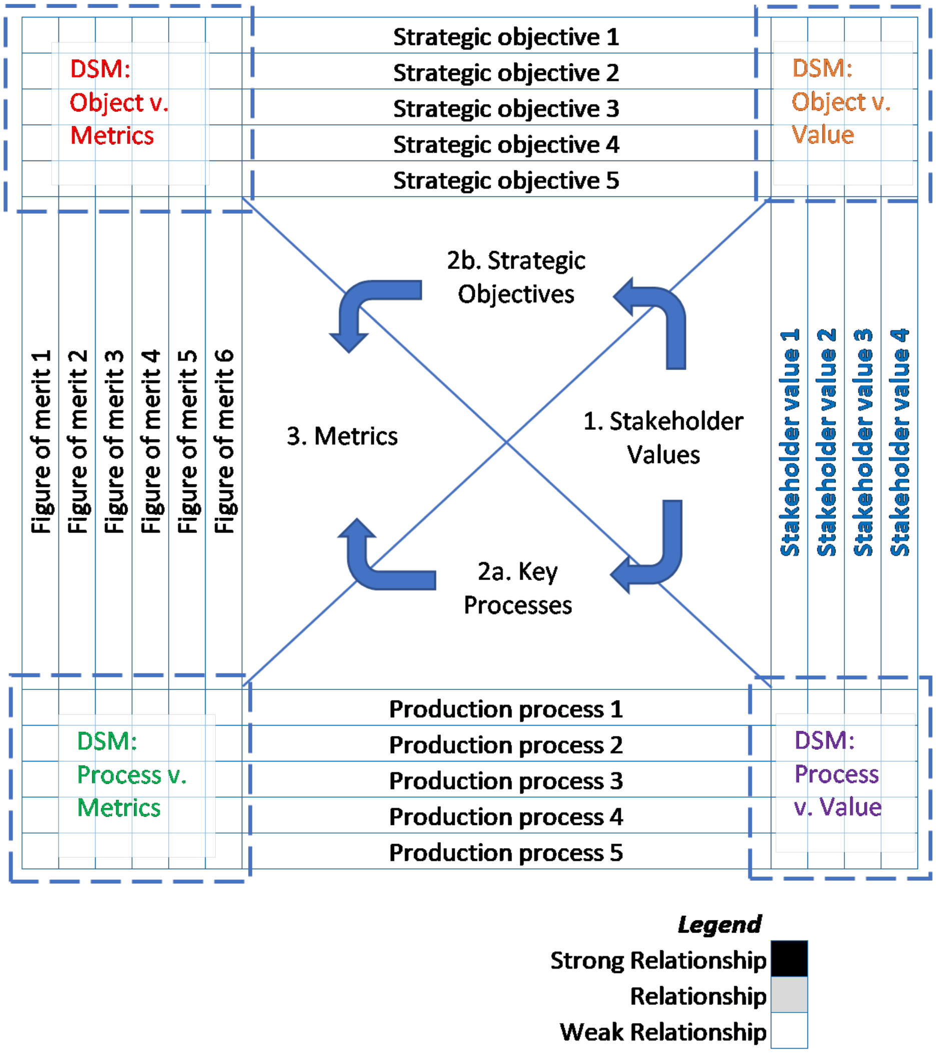


Figure 3-5: X-matrix consisting of 4 DSMs to explore links between stakeholder value, key processes, strategic objectives, and metrics

3.3 Step 3: Explore Prospective Projects

Exploration of prospective projects involves a rigorous search for architectural changes in the form of projects to support the strategic drivers. This search typically consists of technology infusion in the following categories:

- Product performance improvement projects
- Efficiency improvement projects
- Expansion projects

Research should be conducted to explore advancements in the enabling technologies defined in the technology roadmap relationship tree developed in step 1. Sources of technology, as described by de Weck, include, but are not limited to [5]:

- In-house research and development teams
- Private inventors
- Lead users
- Established industrial firms
- Startup companies
- University laboratories
- Government and non-profit research laboratories

Prospective projects represent the design space portion of the analysis, and ideally would include a breadth of projects that collectively support every strategic driver, and notionally improves every key FOM.

3.4 Step 4: Build a Production Throughput Model

Building an accurate production throughput model provides two key benefits:

- The system's throughput response to design variable changes (various combinations of prospective implementation projects)

- Indicators of bottlenecks within the process flow such as localized queue times and high resource utilization

Building the model requires a thorough assessment of the production system including:

- Outlining its production process flow
- Collecting its process time data sets for each process
- Listing resources (staff, equipment, and machines) needed for each process
- Collecting machine reliability data including how often machines malfunction unexpectedly, and the associated downtime
- Collecting scheduled machine maintenance data including the typical cycles times and durations

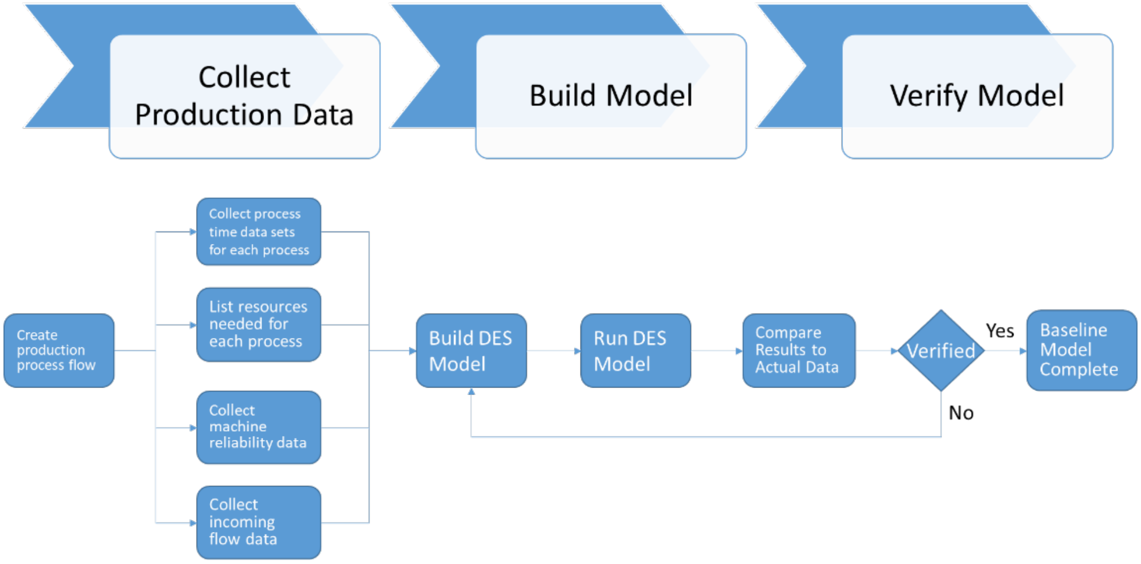


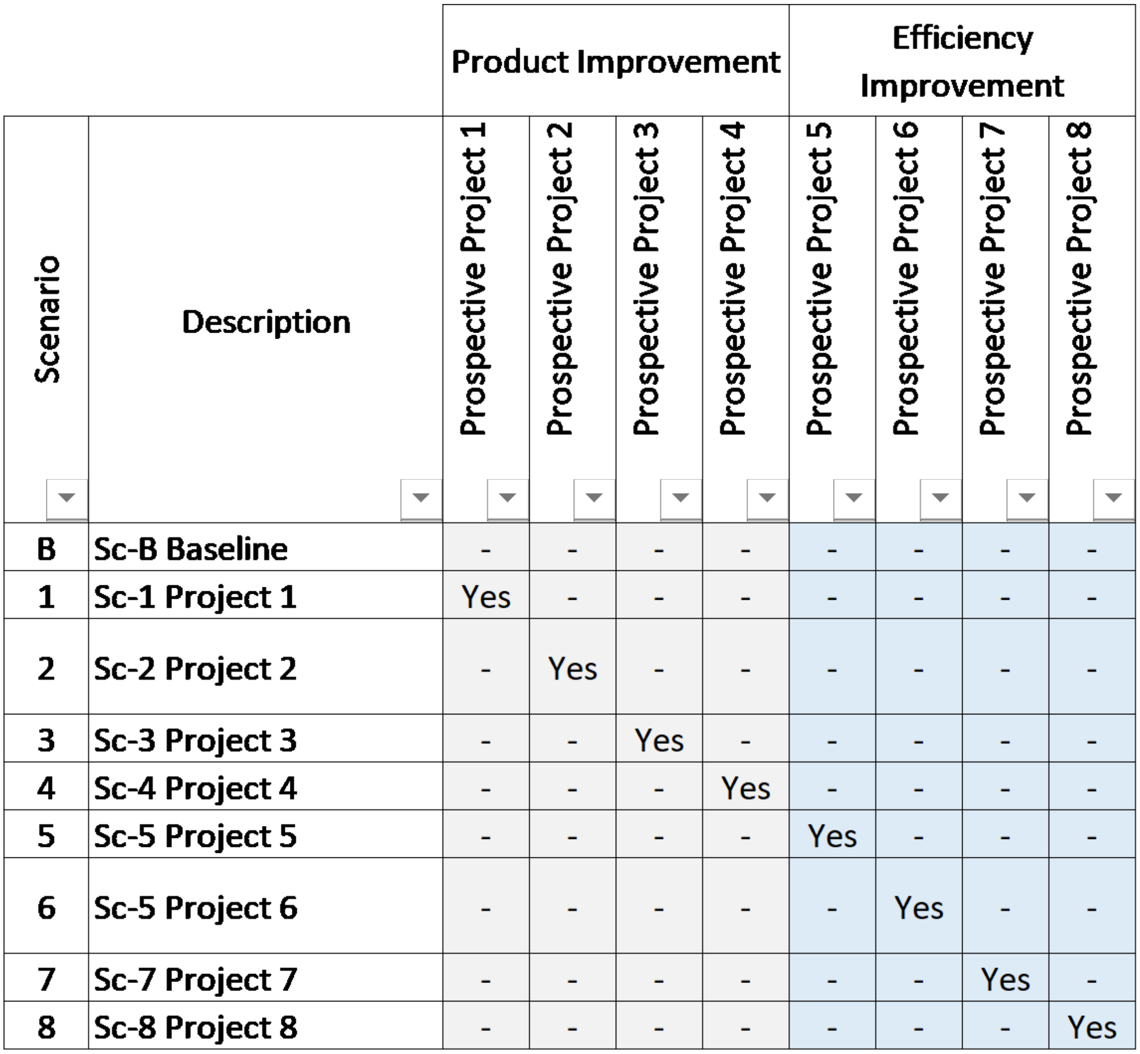
Figure 3-6: Production system modeling process

After collecting production data, a DES-based (Discrete Event Simulation) model can be created to represent the existing production system. Banks et al. describes DES as "the modeling of systems in which the state variable changes only at a discrete set of points in time" [1]. It is a modeling technique employed by the manufacturing sector [16] that can be used to model the operation of production systems since the number of products progressing through the system represents a discrete (as opposed to continuous) variable change over time. Its models are analyzed stochastically by numerical methods and can consider real-world random production system variables such as incoming part arrival times, processing times, and station availability. The case study in chapter 4 demonstrates the use of Rockwell Automation Technologies' Arena DES software package to model a representation of the NIF Optics Recycle Loop production system and its capabilities for identifying process bottlenecks.

After building and running the model, results should be compared to actual production system throughput performance to validate the model. Moreover, the model should be validated for robustness by verifying results against expectations for a number of parameter changes. Parameter changes could include increases or decreases in the number of resources or process times. After verifying that the model is robust and accurately represents the production system, it can serve as the baseline model. Figure 3-6 illustrates the production system model creation and verification process.

Now that a baseline model is established, the focus shifts to generating a list of scenarios. This list of scenarios represents all the project portfolios under consideration and ideally would consist of the full factorial set of all the possible combinations of prospective product improvement and efficiency improvement projects (excluding expansion projects for now). If, for example, 8 prospective projects are considered, then a total of 256 scenarios would be considered since each project represents a binary design choice to either include or exclude. Table 3.2 is an example of 8 scenarios each including just a single prospective project. The scenario list, when fully populated, should consist of 256 scenarios (for 8 prospective projects) each representing a unique project combination. If automated modeling capabilities are limited and running the full factorial set is cost-prohibitive, an orthogonal array can be used to select a subset of scenarios.

Each scenario's result from the DES model should provide indicators of throughput-limiting bottlenecks in the processes flow. These bottlenecks can be alleviated with production facility expansion or scaling efforts to increase resource quantities. If scaling projects are viable options, then each scenario can contain multiple sub-scenarios that incrementally add a single bottleneck-alleviating scaling project. Table 3.3 is an example of multiple DES-guided sub-scenarios.

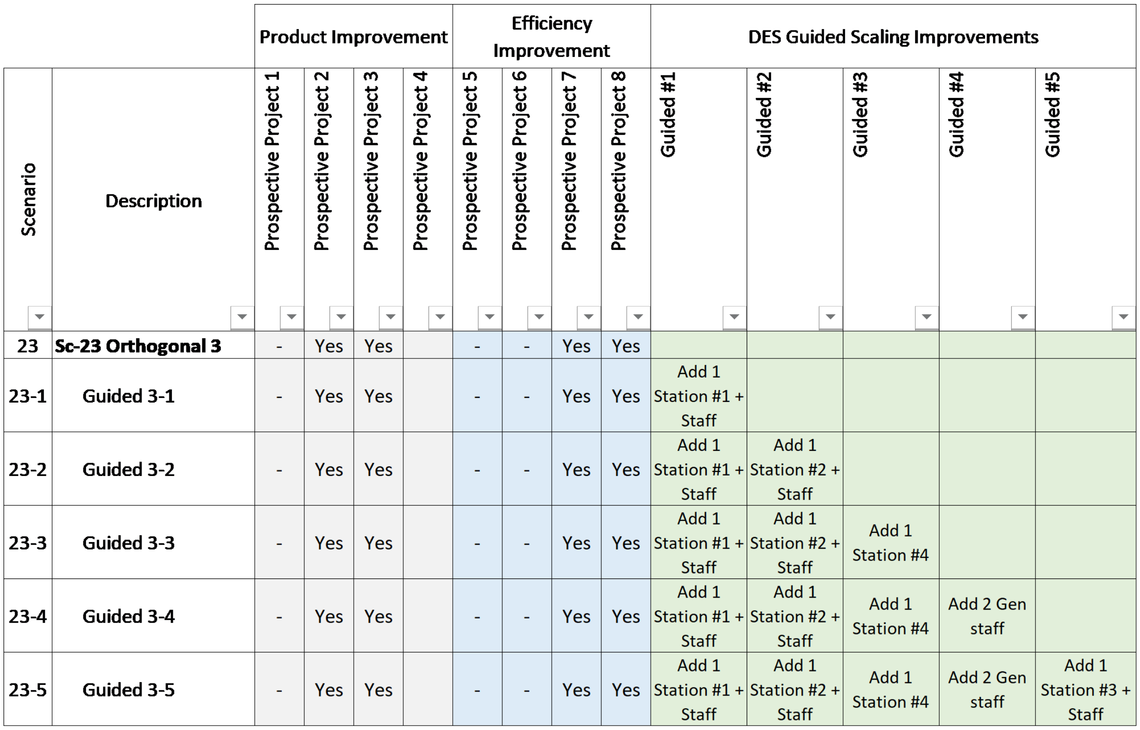


		Product Improvement				Efficiency Improvement			
Scenario	Description	Prospective Project 1	Prospective Project 2	Prospective Project 3	Prospective Project 4	Prospective Project 5	Prospective Project 6	Prospective Project 7	Prospective Project 8
B	**Sc-B Baseline**	-	-	-	-	-	-	-	-
1	**Sc-1 Project 1**	Yes	-	-	-	-	-	-	-
2	**Sc-2 Project 2**	-	Yes	-	-	-	-	-	-
3	**Sc-3 Project 3**	-	-	Yes	-	-	-	-	-
4	**Sc-4 Project 4**	-	-	-	Yes	-	-	-	-
5	**Sc-5 Project 5**	-	-	-	-	Yes	-	-	-
6	**Sc-5 Project 6**	-	-	-	-	-	Yes	-	-
7	**Sc-7 Project 7**	-	-	-	-	-	-	Yes	-
8	**Sc-8 Project 8**	-	-	-	-	-	-	-	Yes

Table 3.2: Example of 8 scenarios each consisting of a single prospective project

3.5 Step 5: Build a Product Performance Model

Typically, product performance FOMs are part of the key FOMs and play a prominent role in stakeholder value assessment. Product performance models are therefore needed to evaluate all scenarios and sub-scenarios. Ideally, product performance



		Product Improvement				Efficiency Improvement				DES Guided Scaling Improvements				
Scenario	**Description**	**Prospective Project 1**	**Prospective Project 2**	**Prospective Project 3**	**Prospective Project 4**	**Prospective Project 5**	**Prospective Project 6**	**Prospective Project 7**	**Prospective Project 8**	**Guided #1**	**Guided #2**	**Guided #3**	**Guided #4**	**Guided #5**
23	**Sc-23 Orthogonal 3**	-	Yes	Yes		-	-	Yes	Yes					
23-1	**Guided 3-1**	-	Yes	Yes		-	-	Yes	Yes	Add 1 Station #1 + Staff				
23-2	**Guided 3-2**	-	Yes	Yes		-	-	Yes	Yes	Add 1 Station #1 + Staff	Add 1 Station #2 + Staff			
23-3	**Guided 3-3**	-	Yes	Yes		-	-	Yes	Yes	Add 1 Station #1 + Staff	Add 1 Station #2 + Staff	Add 1 Station #4		
23-4	**Guided 3-4**	-	Yes	Yes		-	-	Yes	Yes	Add 1 Station #1 + Staff	Add 1 Station #2 + Staff	Add 1 Station #4	Add 2 Gen staff	
23-5	**Guided 3-5**	-	Yes	Yes		-	-	Yes	Yes	Add 1 Station #1 + Staff	Add 1 Station #2 + Staff	Add 1 Station #4	Add 2 Gen staff	Add 1 Station #3 + Staff

Table 3.3: Example of multiple DES-guided sub-scenarios

models would involve science-based, governing mathematical expressions to forecast performance. In practice, however, the underlying scientific principles governing performance may not be well understood. In those cases, empirical data can be used as a basis to assign numerical factors of improvement to baseline performance. Projects that increase performance are assigned factors >1.0 while those that decrease performance (if any) are assigned factors <1.0. If factors of improvement are used, then the resulting factor for a specific performance FOM for a given scenario can be determined by:

$$P_{TOT} = P_1 * P_2 * P_3 * ... * P_n$$

Here, P_1, P_2, P_3, and P_n represent performance factors for each of the n number of prospective projects. Each key product performance FOMs must have a model to output simulated performance for each scenario and sub-scenario.

3.6 Step 6: Build a Cost Model

Cost-related FOMs – project capital expenditures, operating expenditures, project effort, operating effort, etc. – are also typically part of the key FOMs. Cost data from similar legacy projects and equipment offer good bases for estimates. Estimated project costs can then be simply summed to determine the portfolio costs of each scenario and sub-scenario. For costs with baseline values (operating expenditures, operating effort, etc.) where legacy cost data is unavailable or unreliable, costs can be estimated by assigning numerical factors that represent increases or decreases. Projects that increase costs are assigned factors >1.0 while those that decrease cost (if any) are assigned factors <1.0. If factors of improvement are used, then the resulting factor for a specific cost FOM for a given scenario can be determined by:

$$C_{TOT} = C_1 * C_2 * C_3 * ... * C_n$$

Here, C_1, C_2, C_3, and C_n represent cost factors for each of the n number of prospective projects. Each key cost FOM must have a model to output cost for each scenario and sub-scenario.

3.7 Step 7: Assess and Compare Portfolio Options

To assess portfolio options (represented by the list of scenarios and sub-scenarios), stakeholder value is derived using Multi-attribute Utility (MAU) theory to aggregate forecasted utility and estimated costs. Cost in this case can be monetary or effort-related key FOMs but can also be performance-related key FOMs as long as they represent sacrifices to obtain utility improvement.

The first sub-step is to classify the key FOMs as either utility FOMs or cost FOMs. For each of the utility FOMs, assign a weight value that represents the level of importance to the stakeholder. When summed, all the utility weight values should equal 1. For each of the cost FOMs, assign a weight value that again represents the level of importance to the stakeholder. When summed, all the cost weight values should also equal 1. For cases where utility and cost are each defined by a single performance key FOM and a single cost (again, this does not necessarily need to be a monetary cost) key FOM, then applying weights, normalizing (discussed below), and aggregating are unnecessary.

The next sub-step is to normalize the performance and cost data for all the scenarios and sub-scenarios to obtain values between 0 and 1. The normalized value is determined by the function:

$$z_i = \frac{x_i - min(x)}{max(x) - min(x)}$$

$$x = (x_i, ..., x_n)$$

Here, x represents a utility or cost data set and z_i is the i^{th} normalized data. The aggregated utility value (MAU) and aggregated cost value (Cost Factor) for each scenario and sub-scenario are then determined by multiplying the weight by its value for each of the key FOMs and then summing the weighted values. The multi-attribute utility method applied to both the MAU and the Cost Factor for each scenario x is:

$$v(x) = \sum_{i=1}^{n} w_i * v_i(x_i)$$

where w_i is the importance weight, $v_i(x_i)$ is the value for a given scenario for its i^{th} attribute (the key FOMs), and n is the number of attributes [7].

Each scenario can then be represented in single-attribute or multi-attribute tradespace plots to provide visual representations of the best scenario options with respect to budgetary constraints. Figure 3-7 depicts a single-attribute tradespace plot where throughput (a single utility FOM) is represented on the y-axis and project capital expenditures (a single cost FOM) is represented on the x-axis. In this example, the ideal scenario – represented as the utopia point - would produce the greatest throughput at the least cost. The Pareto frontier outlines scenarios with the best value (throughput at a cost). Scenarios that lie below the Pareto Frontier are considered dominated scenarios – scenarios that offer less benefit at the same relative cost as scenarios on the Pareto frontier. Scenarios with DES-guided sub-scenarios can be linked for clarity. A multi-attribute tradespace plot example depicted in figure 3-8 provides similar information but considers aggregated utility and costs.

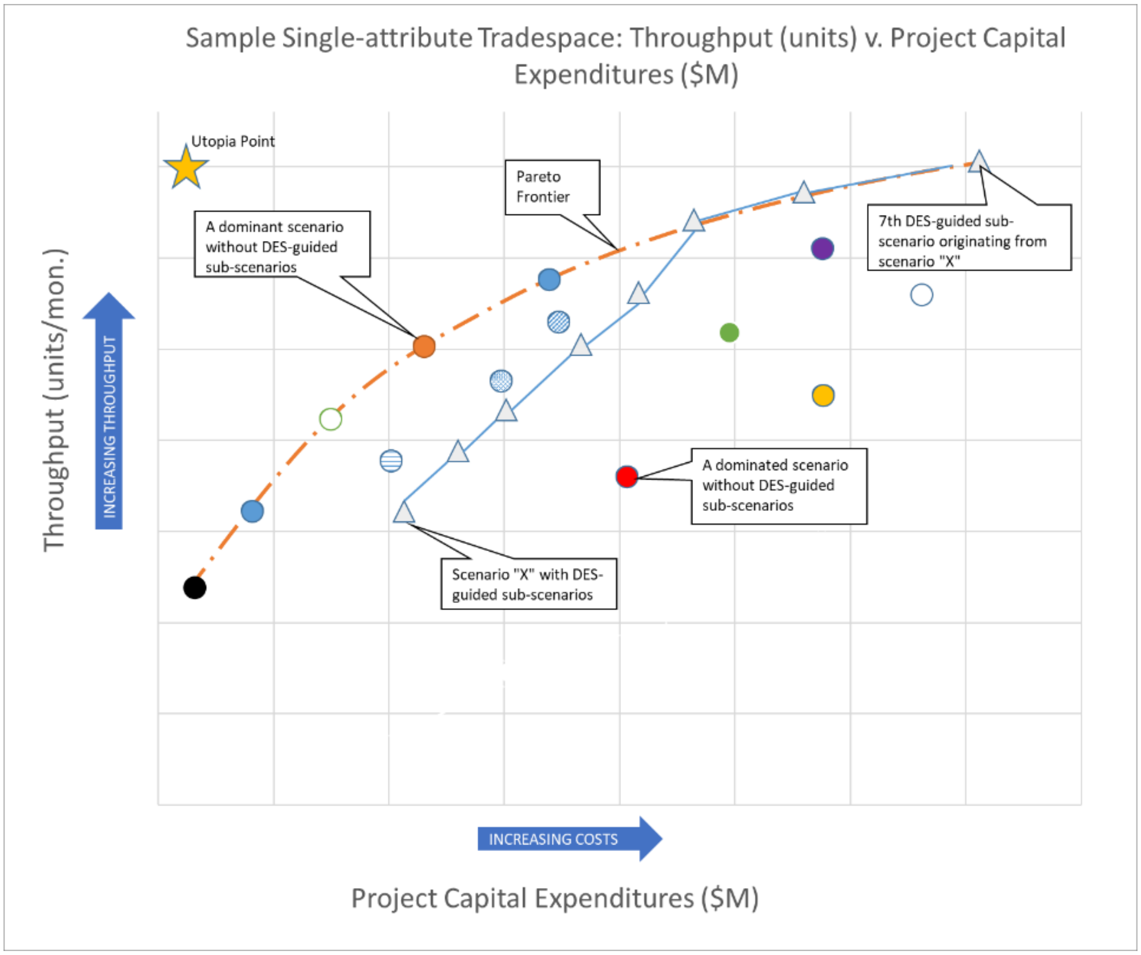


Figure 3-7: Example of a single-attribute tradespace plot of throughput v. project capital expenditures

Costs associated with scenario selections (since they are project-related) typically are not paid all at once and can be phased over time for budget compatibility. Figure 3-9 is an example of a selected scenario consisting of 6 total projects phased over a 20-year period to accommodate annual budgetary constraints. In the chapter 4 case study (section 4.9), the scenario selected consists of 9 total projects with a total estimated portfolio capital expenditure of $13M. The cost is phased over a 20-year period to align with budgetary goals. Project phasing allows for budget compatibility where enterprises can determine timelines based on their budgetary and performance

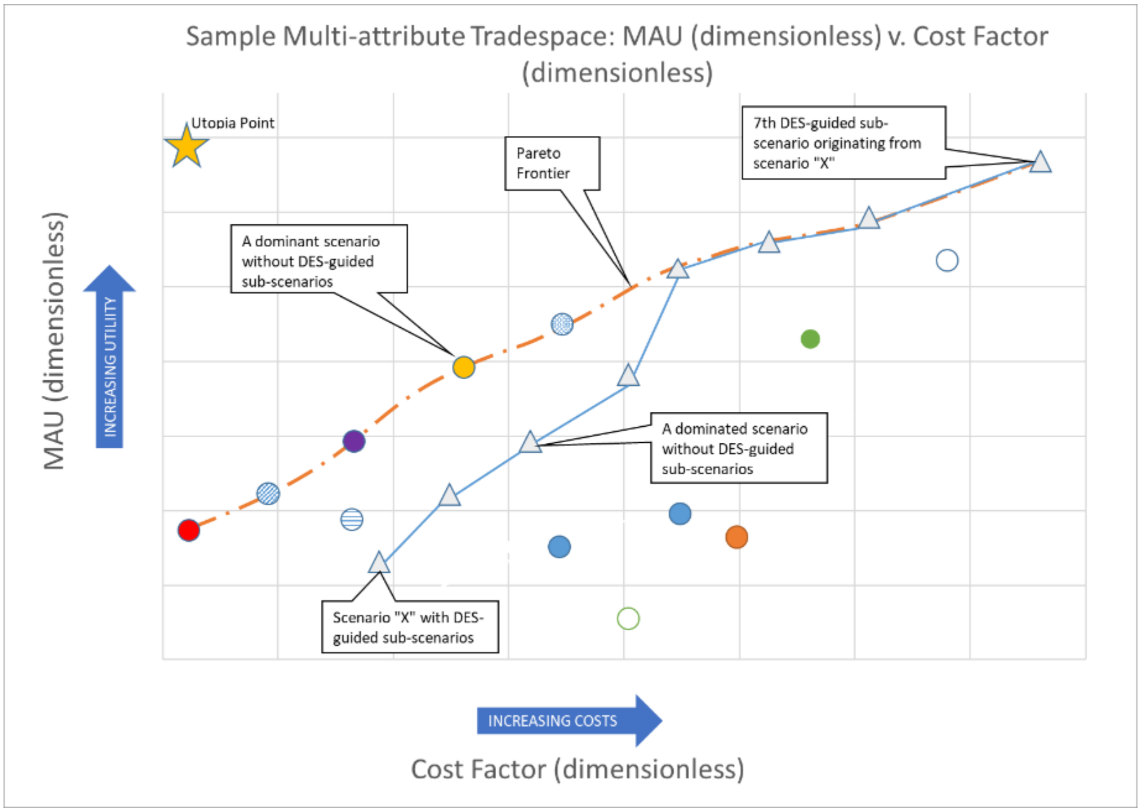


Figure 3-8: Example of a multi-attribute tradespace plot of MAU v. a cost factor

goals.

3.8 Step 8: Select the Project Portfolio

To select the project portfolio, scenarios and sub-scenarios along, or near the Pareto Frontier should be considered. Ultimately, the selection of a single scenario or sub-scenario (representing a project portfolio) depends on the forecasted budget constraints, alignment with strategic drivers, preference for a particular FOM (for cases with aggregated utility or cost), and any intangible factors not considered in the model.

When a project portfolio is selected, creating performance and cost profile plots displaying project costs and performance FOMs over time provides key portfolio metrics. Forecasted annual costs (capital expenditures, staff effort, etc.) and the timing of the forecasted FOM performance improvements (e.g., throughput) after project completions are particularly insightful. When two or more project portfolios are considered, these profile plots can be used to gain additional insights for final portfolio selection. Figure 3-9 is a performance and cost profile plot example showing a sequence of 6 projects staggered over a 20-year period. In this case, the performance FOM displayed is expected to increase after the completion of each project.

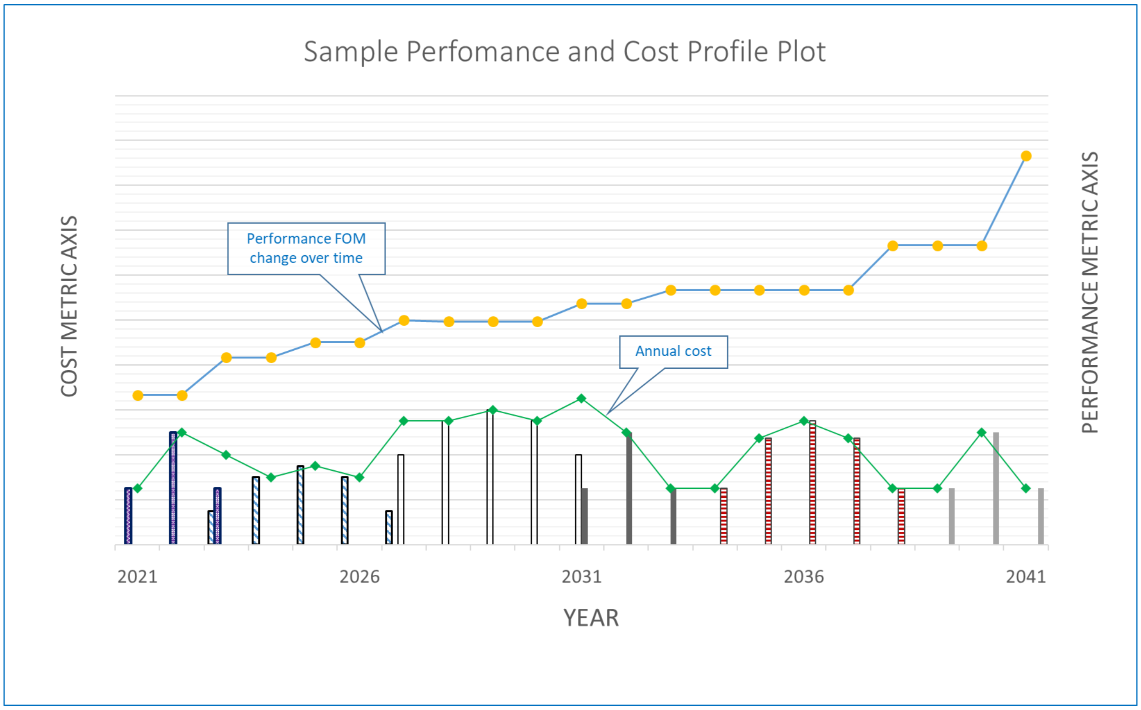


Figure 3-9: An example of a performance and cost profile plot showing project sequencing for a 20-year period

Chapter 4

Case Study: Applying the Proposed Framework to the NIF Optics Recycle Loop

The purpose of this case study is to explore how the systems engineering framework described in chapter 3 can be applied to strategically plan facility upgrade projects for a real-world production system.

4.1 System Background

The National Ignition Facility (NIF), a laser-based inertial confinement fusion research facility located at the Lawrence Livermore National Laboratory (LLNL), conducts fusion power experiments at ultraviolet light fluence levels that exceed the damage threshold of beam conditioning optics causing optic damage and laser performance degradation over time. One of the 192 total Final Optics Assemblies (FOA) in NIF is shown as a schematic in figure 4-1. Within it, the incoming infrared beam (1ω) is converted to ultraviolet light (3ω), passing through a number of transmissive optics - collectively considered the Integrated Optics Module (IOM) - towards a fuel-filled target [24].

To maintain optic health and laser performance, the optics are assessed after each

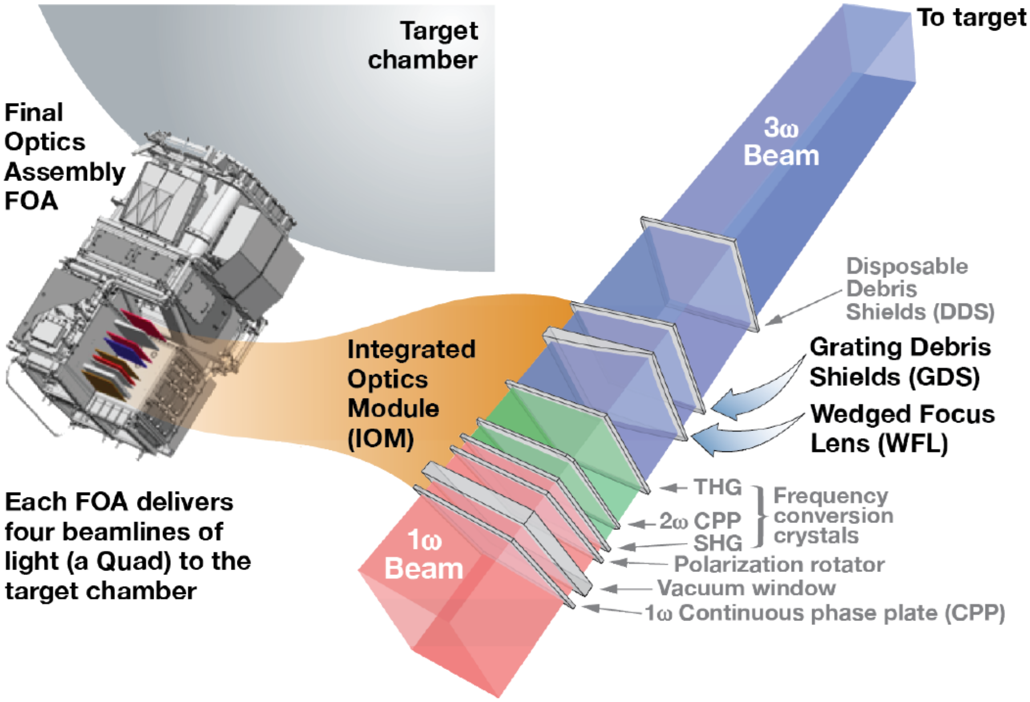


Figure 4-1: Schematic depicting 1 of the 192 NIF Final Optics Assemblies (FOA) housing Integrated Optics Module (IOM) optics used to convert 1ω laser light to 3ω laser light [24]

shot experiment and refurbished if necessary. Figure 4-2 describes the optics recycle process flow at a high level. After NIF fires a laser pulse for shot operations, an in-situ inspection system assesses post-shot optic damage. If optic damage is determined to be below an acceptable threshold, NIF can continue with shot operations without optic-health-related adjustments. If optic damage is determined to exceed established thresholds, the use of localized beam blockers is considered to mask specific damage sites within each damaged optic. If beam blockers are not available or not expected to be effective, the optics are evaluated to determine if they are recyclable. If the damaged optics are recyclable, they are sent to the NIF Optic Recycle Loop (ORL) system. When damaged optics are not recyclable, they are considered for refinishing at the vendor. When optics cannot be refinished, they are removed from service and replaced with new optics [24].

The NIF ORL system is the focus of this case study. It has been in operation for over 20 years now and processed its 10,000th recycled optic in early 2020 [13]. Its

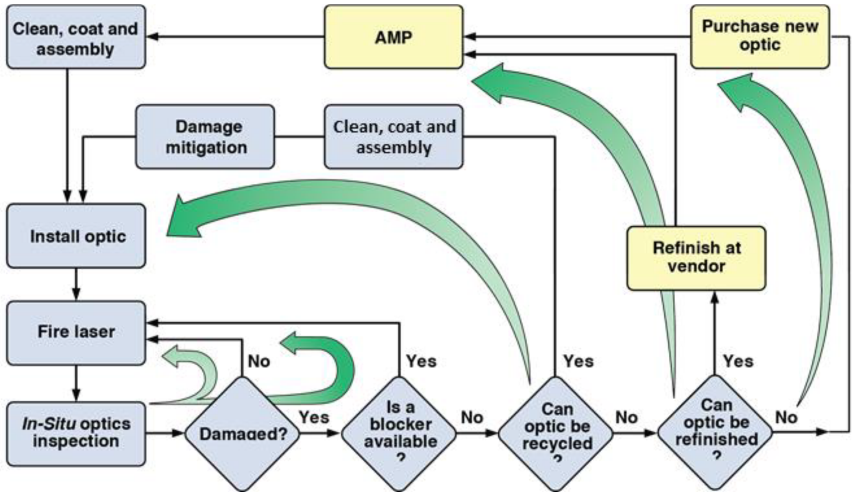


Figure 4-2: A flowchart depicting the NIF Optics Recycle Loop process where damaged optics previously exposed to laser energy in NIF are inspected in-situ, removed from NIF, cleaned, coated, damage mitigated, and reinstalled [24].

complex sociotechnical network of systems consisting of [24]:

- Production staff (machine operators, production supervisors, process engineers)
- Engineering and maintenance staff
- Various chemical and laser-based processing facilities and machines/equipment as shown in figure 4-3
- Process control tools (procedures, work control systems)

are expected to provide value to NIF for the next 20 years or more and are likely to garner significant budget allocations for upgrades for the foreseeable future. When deemed recyclable, large-scale (0.4m x 0.4m) crystals, lenses, and gratings are processed by the system to [24]:

- Clean optics
- Strip coatings
- Apply anti-reflective coatings
- Map damage sites

- Remove damage sites
- Assemble/disassemble optics assemblies
- Inspect and assess optic condition

A systematic value-centric approach and framework to exploring system architecture upgrade options and determining what upgrades to implement over time in the form of a project portfolio would be a valuable decision-making tool for the NIF management team.

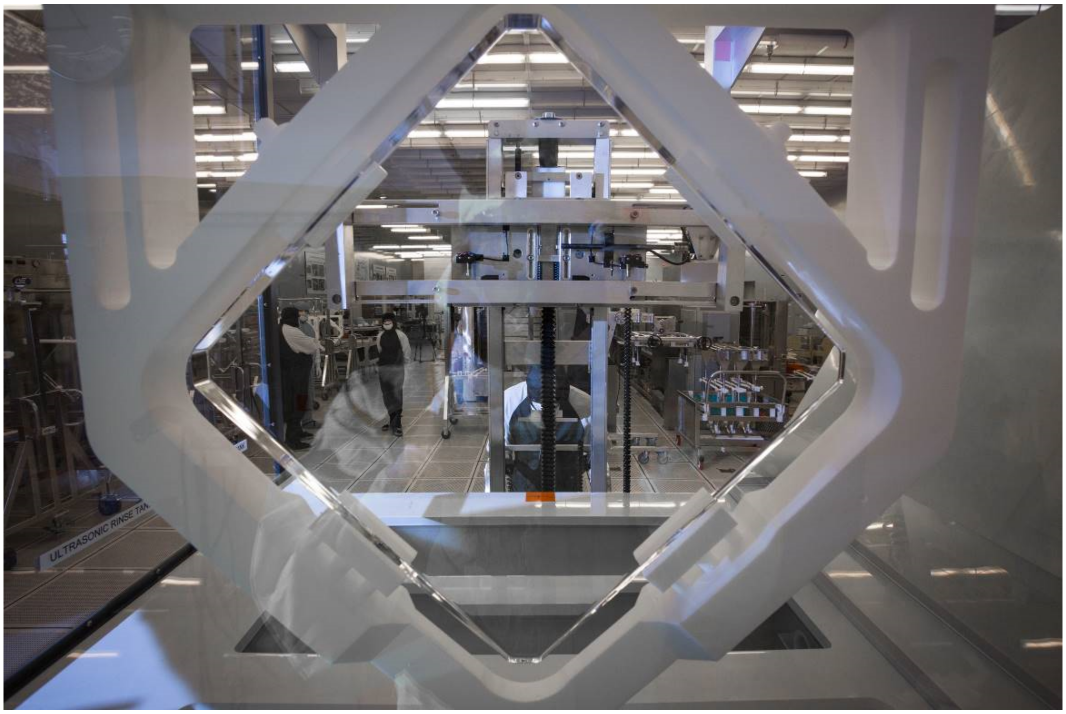


Figure 4-3: A photo taken in one of the NIF optics processing facilities depicting operators processing optics [12]

4.2 Step 1: Explore Current State of the Production System

The NIF Optics Recycle Loop system can be conceptualized as 1 of 3 off-site systems responsible for processing and supplying optics to NIF as shown in the system context diagram (figure 4-4). It receives laser-induced damaged FOA optics from NIF laser beamlines and recycles them for reuse by repairing damage sites. If optics cannot be repaired in the recycle system, they are sent to a substrate supplier for refinishing. Although the recycle loop processes a variety of NIF IOM optics, for this case study, we will only consider the processing of the most commonly recycled optics – the Grating Debris Shield (GDS) and Wedged Focus Lens (WFL) – for simplicity. Accompanying the NIF ORL are the New Optics Processing and Large Optics Processing systems. The New Optics Processing system receives new FOA optic substrates from suppliers and employs many similar processes such as cleaning and coating but does not contain any repair-type processes. The Large Optics Processing System processes and provides large mirrors and amplifiers to on-site NIF optics assembly areas. Collectively, all 3 systems represent the NIF Optics Production System.

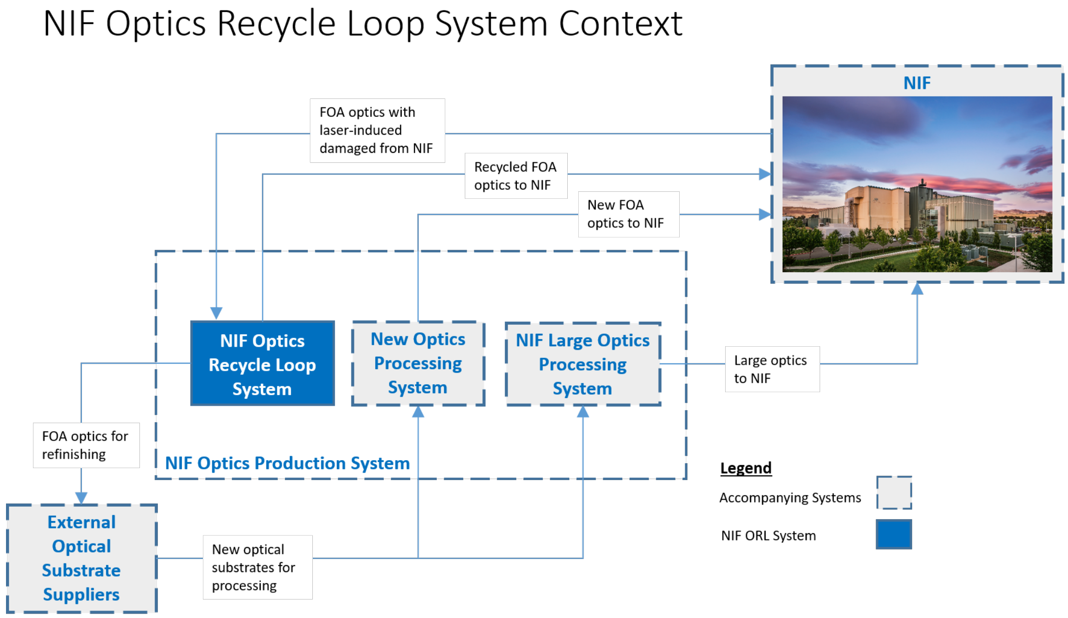
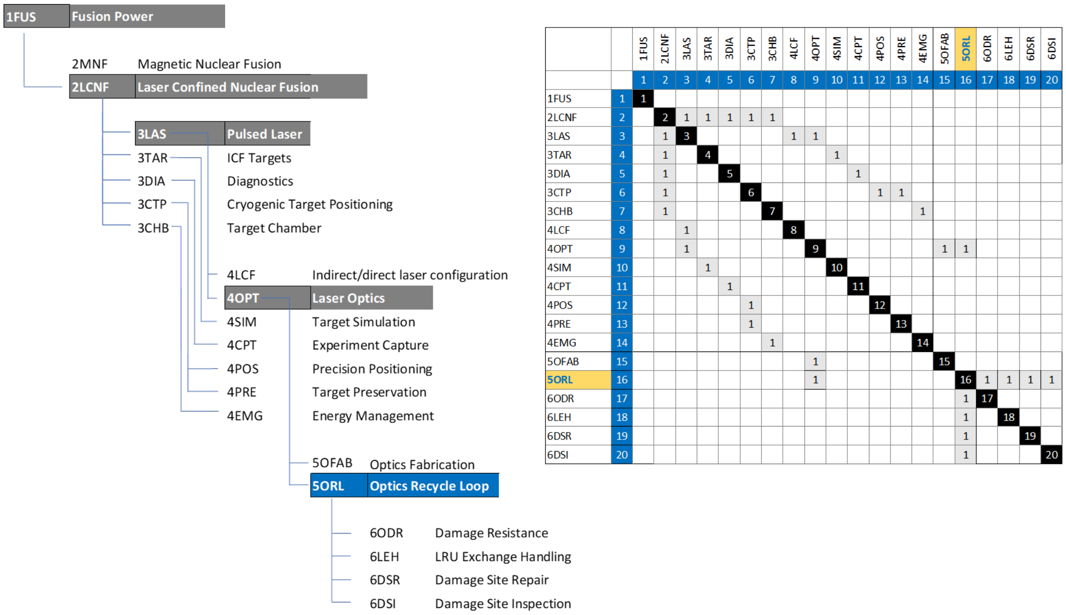


Figure 4-4: System context diagram for the NIF Optics Recycle Loop system showing its accompanying processing systems and depicting optics flow. The NIF Optics Production System delivers finished optics ready for installation to NIF. [12]

4.2.1 Technology Roadmap

The NIF ORL system's technology roadmap is a level 5 technology that can be traced up to the level 1 *Fusion Power* technology roadmap. Figure 4-5 highlights some of the dependent technology roadmaps for *Fusion Power* to better understand the role of the NIF ORL. The two main branches of fusion technology development are laser-based inertial confinement and tokamak-based magnetic confinement methods. NIF, Laser MegaJoule, and the Shen-Guang III are all examples of laser-based experimental facilities while ITER and SPARC are examples of two tokamak-based magnetic confined fusion experimental facilities under development. Laser-driven systems depend on a number of level 3 technology roadmaps such as *ICF targets*, *Diagnostics*, *Cryogenic Target Positioning*, and *Pulsed Laser*. One of the critical laser capabilities identified by NIF researchers in their efforts to demonstrate fusion technology is the delivery of laser energy to the target at elevated fluence levels (exceeding the damage threshold on the laser optics) which is limited by optics performance-related *Laser Optics* technology and optics availability related to *Optics Recycle Loop* technologies [24].



		1FUS	2LCNF	3LAS	3TAR	3DIA	3CTP	3CHB	4LCF	4OPT	4SIM	4CPT	4POS	4PRE	4EMG	5OFAB	5ORL	6ODR	6LEH	6DSR	6DSI
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1FUS	1	1																			
2LCNF	2		2	1	1	1	1	1													
3LAS	3		1	3					1	1											
3TAR	4		1		4						1										
3DIA	5		1			5						1									
3CTP	6		1				6						1	1							
3CHB	7		1					7							1						
4LCF	8			1					8												
4OPT	9			1						9						1	1				
4SIM	10				1						10										
4CPT	11					1						11									
4POS	12						1						12								
4PRE	13						1							13							
4EMG	14							1							14						
5OFAB	15									1						15					
5ORL	16									1							16	1	1	1	1
6ODR	17																1	17			
6LEH	18																1		18		
6DSR	19																1			19	
6DSI	20																1				20

Figure 4-5: Optics Recycle Loop technology roadmap DSM and technology dependence tree showing the relationship to higher-level technologies leading to fusion power technology and lower level dependent technologies

4.2.2 Describe the System Architecture

The NIF ORL's architecture can be described by the 2 Object Process Methodology (OPM) diagrams shown in figures 4-6 and 4-7. The primary process of the system is the recycling of the WFL and GDS optics that are damaged by the NIF laser system after a number of laser shot experiments above the optics damage threshold. The ***Recycling*** process can be expanded to seven lower-level processes [24, 10]:

- **Disassembling** – Manually disassembling optic assemblies referred to as LRUs (Line Replaceable Units) to extract the optics from transport cases and their frame structures that serve as the mechanical interfaces to the NIF Final Optics Assembly (FOA) with the use of assembly stations

- **Packaging** – Manually assembling the optic to their LRUs and inserting them into transport cases with the use of assembly stations

- **Cleaning**- An automated process where aqueous solutions are used to precision clean fused-silica optics such as the GDS, WFL, and potentially the Fused Silica Debris Shield (FSDS)

- **Coating**- Automated processes to apply sol-gel anti-reflection coatings to fused-silica optical surfaces

- **Stripping**- An automated process where aqueous solutions are used to strip the sol-gel anti-reflection coating from fused-silica optics such as the GDS, WFL, and potentially the FSDS

- **Inspecting**- Automated and manual processes to assess an optic's recyclability (in terms of damage), to identify and characterize flaws, and to validate optic performance

- **Damage Site Removal** – An automated process where fused-silica optic damage sites are repaired using focused CO_2 lasers to ablate and reshape the site

The system also contains processes to modernize the system and to maintain and repair the production equipment. These processes are driven by engineers, optics researchers, and technicians.

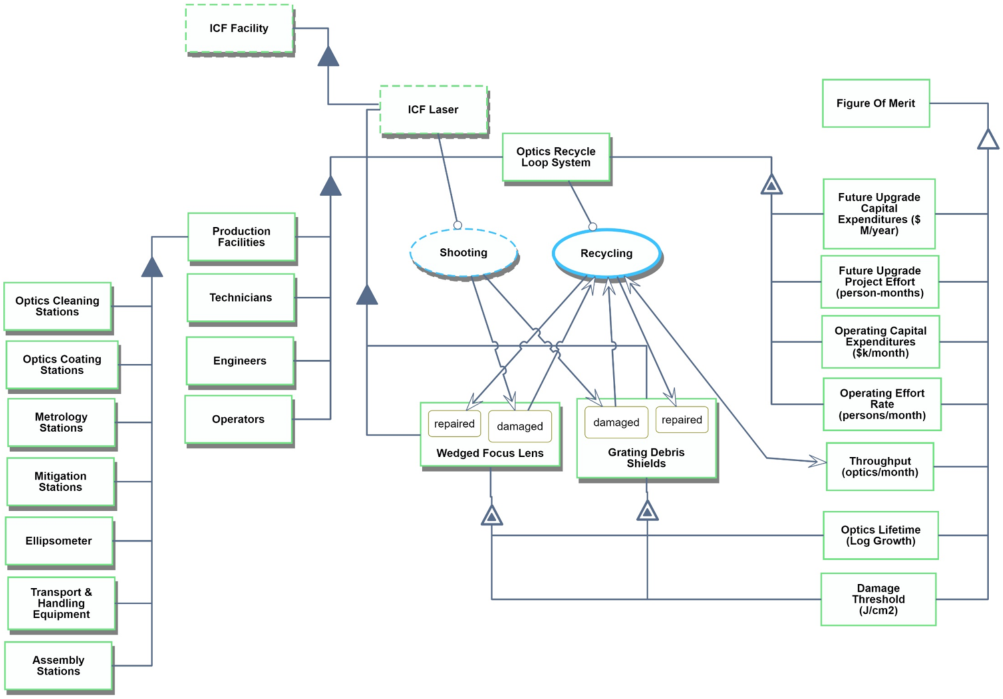


Figure 4-6: The NIF Optics Recycle Loop's system architecture described using an OPM diagram emphasizing figures of merit, objects of form, and high-level processes

4.3 Step 2: Envision the Future Landscape

From an ecosystem perspective, NIF ORL sustainability relies heavily on the future value provided to the NIF system. To better understand how to best prepare for the future, we will envision the future landscape by exploring the next potential steps for NIF and general trends in Inertial Confinement Fusion (ICF) development. In a recent paper describing U.S. ICF progress, researchers (including researchers from LLNL) report significant progress towards ignition with more than a 20x increase in fusion neutron yield when compared to initial yields just after completion of the facility in 2010 [8]. To further increase the performance of the current implosions,

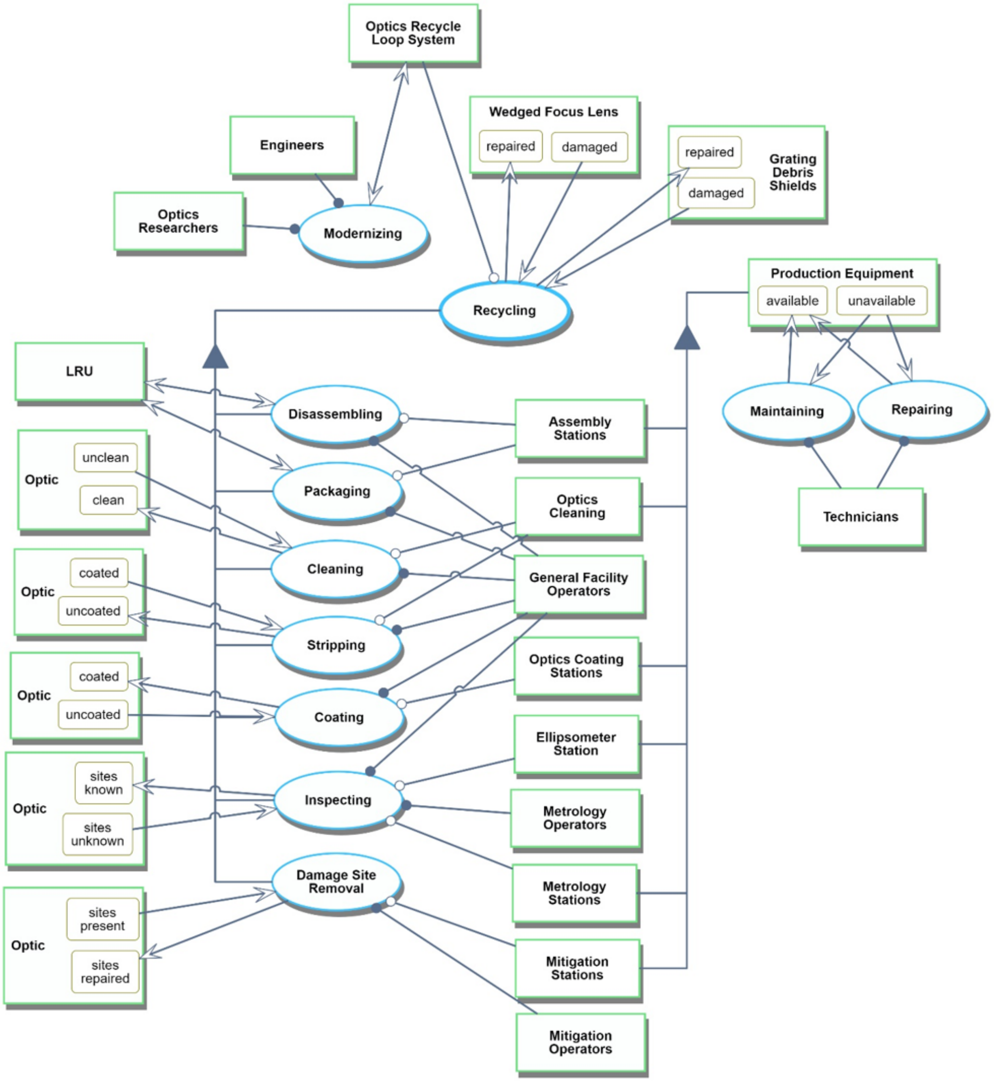


Figure 4-7: The NIF Optics Recycle Loop's system architecture described using a lower-level OPM diagram focusing on the system objects and sub-processes of the *Recycling* process

researchers are considering scaling up the ICF targets in the future [8]. Upsizing targets to the desired scale however would require almost doubling the current NIF laser energies (1.8-2 MJ) to the range of 3.5-4 MJ to achieve gains greater than 1 [8]. The desire to operate at greater pulsed laser energies is not a new concept as evidenced by the construction of NIF after its two predecessor facilities (the Shiva and Nova lasers) produced lower laser energies using fewer beamlines.

Due to the desire to conduct experiments at much greater laser energy levels, we can envision a future landscape where the NIF GDS and WFL exchange rates significantly increase due to future upscaling of the number of beamlines to achieve greater laser energies required to experiment with larger targets. We can also envision a future landscape where the benefits of exposing the optics to even greater damage-inducing fluences (and therefore shortening their lifetimes) to experiment at greater laser energies outweigh the costs resulting again in much greater optics exchange rates. Another potential scenario in the longer term could also be the construction of NIF's successor with even greater laser energy specifications and more beamlines. Based on the future envisioned landscapes, we can surmise that offering optics that enable ICF experiments at elevated laser energies in the future aligns with the future needs of ICF research in general. To sustain future demand for the NIF ORL system, we must strategically explore initiatives to both increase the optic's damage threshold and the facility's throughput capability by implementing mature technologies.

4.3.1 Identify Stakeholders and Key FOMs

Table 4.1 lists each system stakeholder, their needs, their value contributed to the system, and the value delivered to them by the system. Although every stakeholder delivers value to the system and is important, the funding and overall strategy provided to the system by the *NIF Senior Management Team* is critical to sustaining the system. They are therefore considered the most important stakeholder as shown in the stakeholder importance mapping in Figure 4-8. At a high level, their main need from the NIF ORL is the capability to cost-effectively process and provide NIF with optics for sustained operation.

The *NIF Operations Team* and the *NIF ICF Researchers* can be considered the system's end-users of its optics produced and are therefore also mapped as very important stakeholders. The *NIF ICF Researchers'* main needs from the system are optics performance and optics availability attributed to the laser driver's performance to allow for a greater range of laser pulse parameter exploration for conducting shot experiments. The *NIF Operations Team's* main need is optics availability to replenish damaged optics on NIF to enable continued operation and maintain their shot schedule. Although the system is performing well in providing value to these stakeholders, it can provide even greater value by supplying optics that allow for higher-energy shot experiments. Based on the mapping of stakeholder importance and the potential to deliver even greater value, the NIF ORL system should be focusing on efforts to improve the value delivered to the *NIF Senior Management Team*, the *NIF Operations Team*, and *NIF ICF Researchers.* Figure 4-9 provides an overview of the stakeholder value network where the *Optics Production Management Team* serves as the main value delivery interface between the external stakeholders and the internal stakeholders assigned to roles within the system. To provide greater value to the most important stakeholders, the NIF ORL should be considering projects to improve in the following stakeholder value areas:

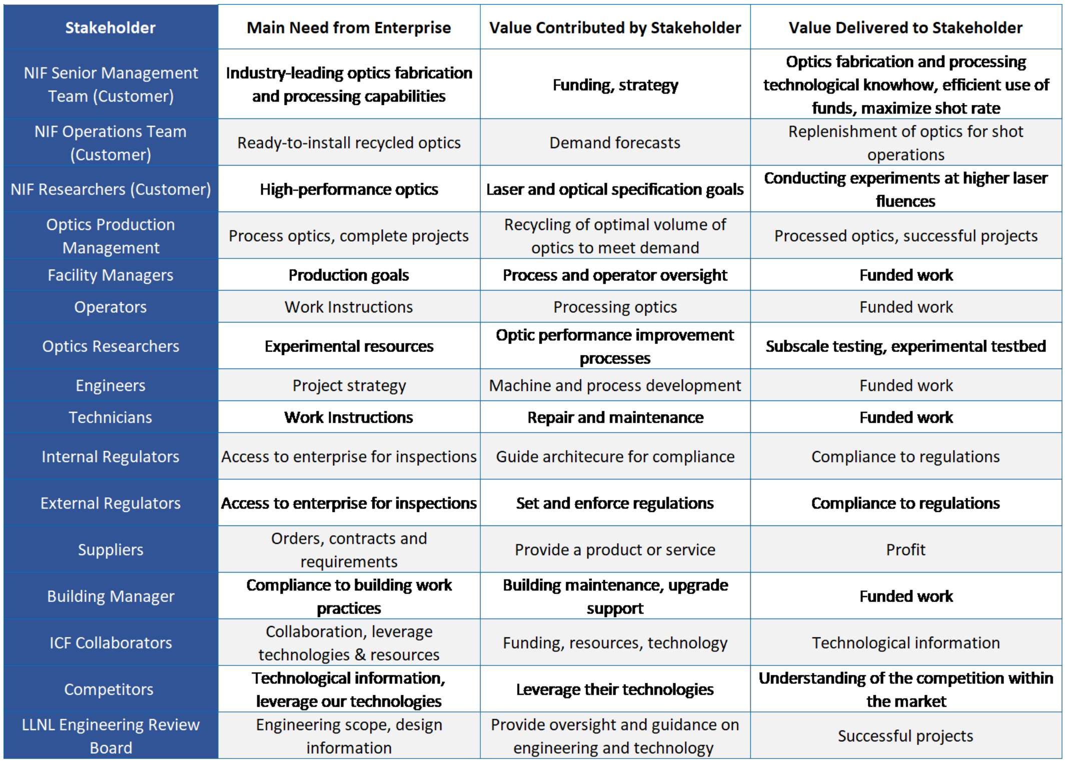
- Increase laser pulse energy
- Replenishment of optics
- Reduce NIF operating costs
- Maximize shot rate

These key stakeholder values and their relationships to potential strategic objectives and key processes are shown in the X-matrix in figure 4-10. These key stakeholder values are strongly tied to the cleaning, coating, mitigation, and metrology processes. They are also strongly tied to 4 of the 5 potential strategic objectives:

- Improve machine reliability

- Improve optics performance
- Improve process efficiency
- Scale the facility to meet demand

When exploring the relationship between potential metrics, the key processes and the potential strategic objectives, four project and operating cost metrics along with *optics damage threshold*, and *optics throughput* have the strongest relationships and should be considered the key FOMs (figures of merit) for the system's technology as they are derived from the value delivered to the most important stakeholders. Table 4.2 shows a full list of FOMs considered and their descriptions.



Stakeholder	Main Need from Enterprise	Value Contributed by Stakeholder	Value Delivered to Stakeholder
NIF Senior Management Team (Customer)	**Industry-leading optics fabrication and processing capabilities**	**Funding, strategy**	**Optics fabrication and processing technological knowhow, efficient use of funds, maximize shot rate**
NIF Operations Team (Customer)	Ready-to-install recycled optics	Demand forecasts	Replenishment of optics for shot operations
NIF Researchers (Customer)	**High-performance optics**	**Laser and optical specification goals**	**Conducting experiments at higher laser fluences**
Optics Production Management	Process optics, complete projects	Recycling of optimal volume of optics to meet demand	Processed optics, successful projects
Facility Managers	**Production goals**	**Process and operator oversight**	**Funded work**
Operators	Work Instructions	Processing optics	Funded work
Optics Researchers	**Experimental resources**	**Optic performance improvement processes**	**Subscale testing, experimental testbed**
Engineers	Project strategy	Machine and process development	Funded work
Technicians	**Work Instructions**	**Repair and maintenance**	**Funded work**
Internal Regulators	Access to enterprise for inspections	Guide architecure for compliance	Compliance to regulations
External Regulators	**Access to enterprise for inspections**	**Set and enforce regulations**	**Compliance to regulations**
Suppliers	Orders, contracts and requirements	Provide a product or service	Profit
Building Manager	**Compliance to building work practices**	**Building maintenance, upgrade support**	**Funded work**
ICF Collaborators	Collaboration, leverage technologies & resources	Funding, resources, technology	Technological information
Competitors	**Technological information, leverage our technologies**	**Leverage their technologies**	**Understanding of the competition within the market**
LLNL Engineering Review Board	Engineering scope, design information	Provide oversight and guidance on engineering and technology	Successful projects

Table 4.1: A list of the NIF Optics Recycle Loop Stakeholders with descriptions of their main needs from the enterprise, their value contributed, and the value delivered by the system

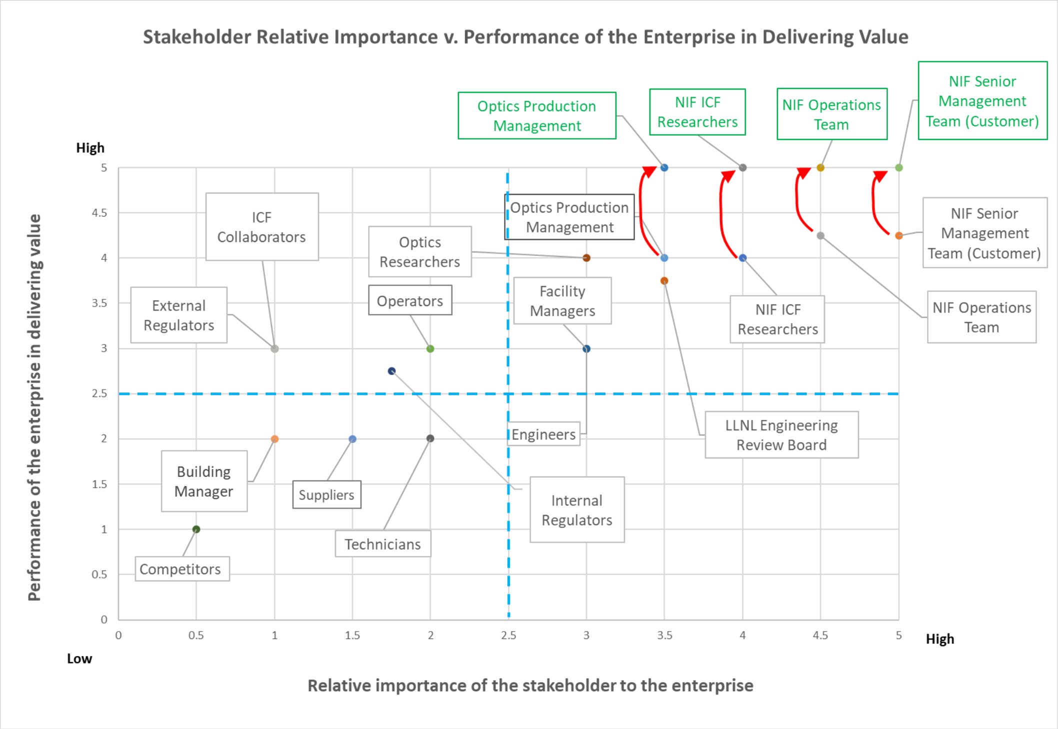


Figure 4-8: A plot of *Stakeholder Relative Importance v. Performance of the Enterprise in Delivering Value*. The most important stakeholders are highlighted in green with goals to improve value delivery in the future depicted with red arrows.

ID	FOM	Units	Description
1	**Optics Throughput**	optics/month	Maximum GDS and WFL optics production rate per month
2	**Damage Threshold**	J/cm^2	Maximum fluence before damage initiation sites appear
3	**Project Capital Expenditures**	$M (USD)	Cost of capital equipment related to a specific project or a number of projects
4	**Project Effort**	person-months	Staffing effort related to specific project or a number of projects
5	**Operating Capital Expenditure Ratio**	NA	Ratio representing an increase or decrease to the baseline cost of operating equipment
6	**Operating Effort Ratio**	NA	Ratio representing an increase or decrease to the baseline operating effort
7	Optics Lifetime	Log Growth	Metric derived from LLNL studies in fused silica damage site growth rate used to track optic's lifetime. Log growth is a function of the laser pulse's total fluence exposed to the optic and the optic's damage threshold.
8	Production Yield	%	Percentage of successfully processed conforming parts with respect to all parts attempted
9	Availability	%	Percentage of time when the full system is available for processing with respect to total operational time planned

Table 4.2: A list of FOMs (figures of merit) used to describe the system's technological progress. FOMs 1-6 represent the key system FOMs

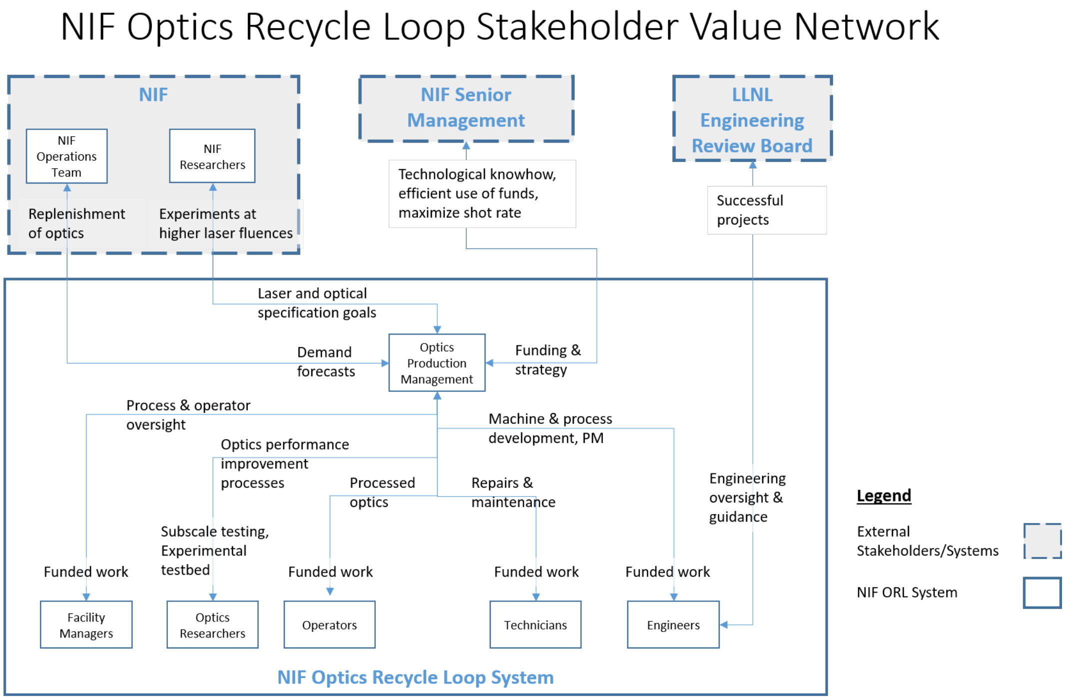
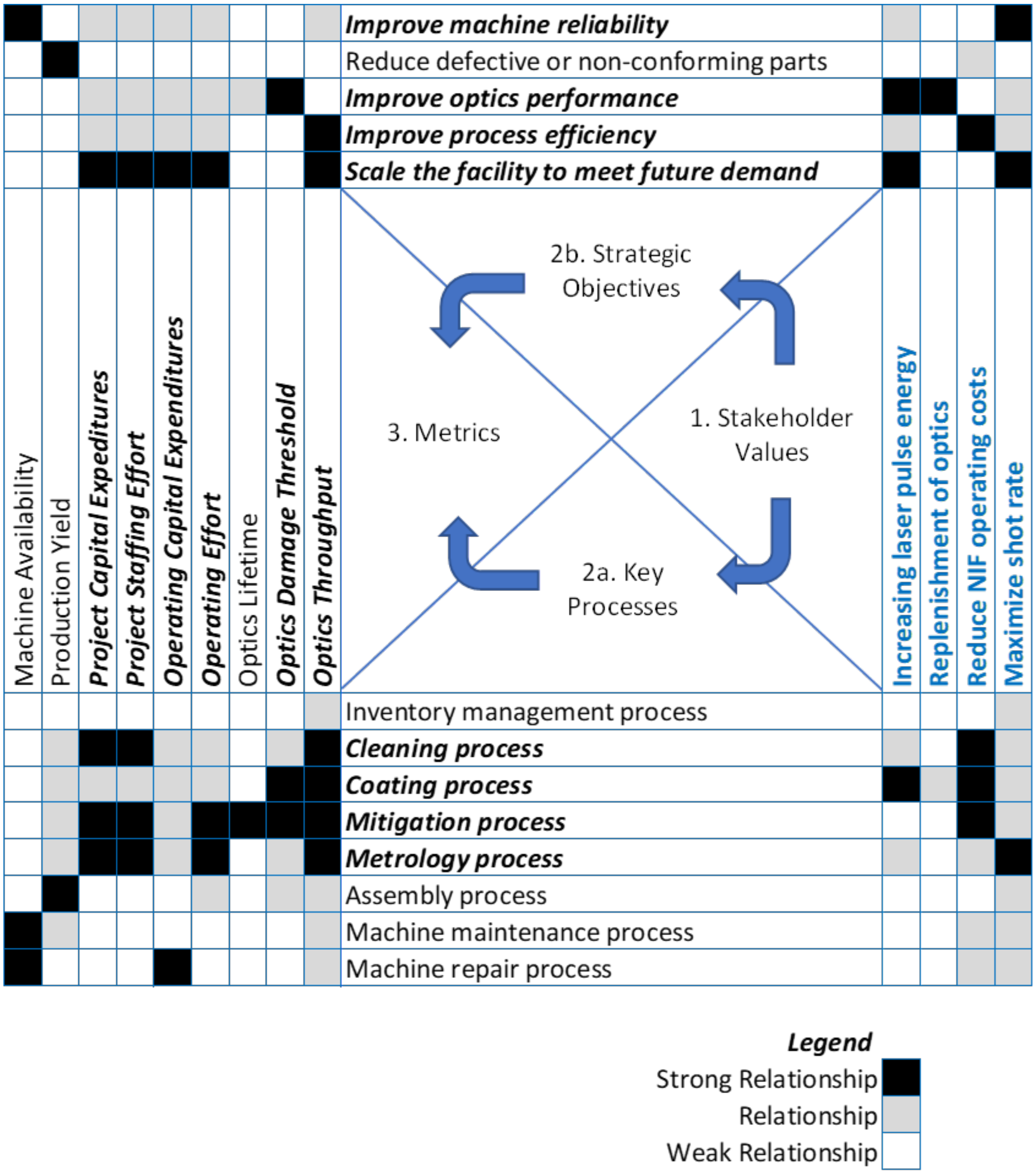


Figure 4-9: A schematic depicting the NIF Optics Recycle Loop's stakeholder value network showcasing delivery and receipt of primary benefits for the key stakeholders

4.3.2 Strategic Drivers

The NIF ORL enterprise plays a pivotal role in supporting NIF's mission of achieving fusion ignition as one of its key enabling technologies linked to laser driver performance. Helping NIF progress towards ignition by enabling higher energy shot experiments is the primary strategy to the sustainability of the NIF ORL enterprise. In the near term, the strategic driver is to improve throughput capacity by implementing select process efficiency technologies to help offset the potential throughput reduction associated with new performance-improving processes by 2023. Ideally, throughput capacity-improving projects would be fully implemented prior to adopting processes aimed at improving the FOA optics damage threshold to > 5 J/cm^2 by 2025. In the long term (by 2041), the strategic driver is to significantly increase throughput to $>$ 200 optics/month by selectively scaling the facilities and their resources to align with the anticipated increase in demand. The strategic drivers and targets summarized in table 4.3 provide guidance towards the exploration of potential project options to



	Machine Availability	Production Yield	***Project Capital Expeditures***	***Project Staffing Effort***	***Operating Capital Expenditures***	***Operating Effort***	Optics Lifetime	***Optics Damage Threshold***	***Optics Throughput***	**Increasing laser pulse energy**	**Replenishment of optics**	**Reduce NIF operating costs**	**Maximize shot rate**
Improve machine reliability	■		▨	▨	▨	▨			▨	▨			■
Reduce defective or non-conforming parts		■										▨	
Improve optics performance			▨	▨	▨	▨	▨	■		■	■		▨
Improve process efficiency			▨	▨	▨	▨			■	▨		■	▨
Scale the facility to meet future demand			■	■	■	■			■	■			■

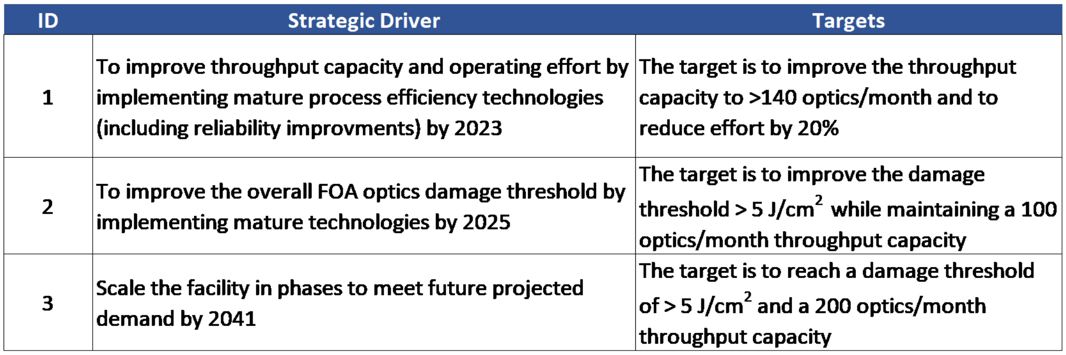
	Machine Availability	Production Yield	***Project Capital Expeditures***	***Project Staffing Effort***	***Operating Capital Expenditures***	***Operating Effort***	Optics Lifetime	***Optics Damage Threshold***	***Optics Throughput***	**Increasing laser pulse energy**	**Replenishment of optics**	**Reduce NIF operating costs**	**Maximize shot rate**
Inventory management process									▨				▨
Cleaning process		▨	■	■	▨	▨		▨	■	▨		■	▨
Coating process		▨	▨	▨	▨	▨		■	■	■	▨	■	▨
Mitigation process		▨	■	■	▨	■	■	■	■			■	▨
Metrology process		▨	■	■	▨	■		▨	■	▨		▨	■
Assembly process		■				▨		▨	▨				▨
Machine maintenance process	■	▨							▨			▨	▨
Machine repair process	■				■				▨			▨	▨

Legend

Strong Relationship	■
Relationship	▨
Weak Relationship	

Figure 4-10: An X-matrix used to better understand the relationships between stakeholder values, strategic objectives, metrics, and key processes. The items in bold represent relationships with the strongest ties to stakeholder values and represent high-value areas for improvement.

help deliver on this overall strategy.



ID	Strategic Driver	Targets
1	To improve throughput capacity and operating effort by implementing mature process efficiency technologies (including reliability improvments) by 2023	The target is to improve the throughput capacity to >140 optics/month and to reduce effort by 20%
2	To improve the overall FOA optics damage threshold by implementing mature technologies by 2025	The target is to improve the damage threshold > 5 J/cm^2 while maintaining a 100 optics/month throughput capacity
3	Scale the facility in phases to meet future projected demand by 2041	The target is to reach a damage threshold of > 5 J/cm^2 and a 200 optics/month throughput capacity

Table 4.3: A list of strategic drivers derived from stakeholder values consisting of initially improving throughput with efficiency improvements, then implementing optics performance improvement projects to improve optics damage threshold, and finally, scaling the facility to boost throughput

4.4 Step 3: Explore Prospective Projects

As outlined in the strategic drivers, we must consider three types of potential projects for the NIF ORL portfolio:

- Product Improvement
- Product Efficiency
- Facility Scaling

Each potential project considered should have a significant impact on either throughput (FOM1) or damage threshold (FOM2). The breadth of potential projects will be combined strategically to create a number of scenarios that represent NIF ORL project portfolio options to consider over the next 20 years.

4.4.1 Product Improvement Initiatives

Driven by the desire to operate ICF laser drivers at higher laser energy levels, researchers at LLNL and the French Alternative Energies and Atomic Energy Commission (CEA) explore technology to improve optics performance. These technologies aim to improve optics damage threshold (FOM2) and represent potential technology implementation projects due to their high technology readiness levels.

Fused Silica Debris Shield Implementation Project

Researchers at NIF propose the addition of a fused silica debris shield (FSDS) optic downstream of the GDS optic to help limit the number of damage sites caused by material ejected from the input side of Disposable Debris Shields (DDS) during high-energy laser shots. Subscale laboratory tests and full-scale experiments on NIF indicate that the addition of this optic has the potential to reduce the amount of GDS damage sites caused by particle debris contamination from DDS Input Surface Bulk Eruptions (ISBE). The schematic shown in figure 4-11 shows 2 configurations depicting ISBE particle migration (red stars and arrows) with and without the new FSDS optic. Based on progress reports by NIF researchers indicating that this technology has been tested on NIF, we will consider this to be mature technology ready for consideration as a potential implementation project to the Optics Recycle Loop (ORL) [3, 15].

Implementation of this technology however places additional demand on the ORL system to recycle FSDS optics in addition to GDS and WFL optics and will reduce the GDS and WFL throughput. In addition, implementing the FSDS likely requires the development of new tooling and the modification of processing machines to support new size constraints or process variations.

AR-GDS Implementation Project

In 2017, NIF researchers reported a significant improvement to GDS optic performance by adding an Anti-Reflective (AR) coating (as shown in figure 4-11) to the output side of the optic containing the diffractive grating surface. Researchers theorized that adding a colloidal silica particle coating would both increase the laser energy transmitted through the optic and reduce the number of damage sites induced by the reflected light from the exit surface. Full-scale experiments on NIF using the AR-coated GDS optics proved the theory's efficacy and technology readiness level for

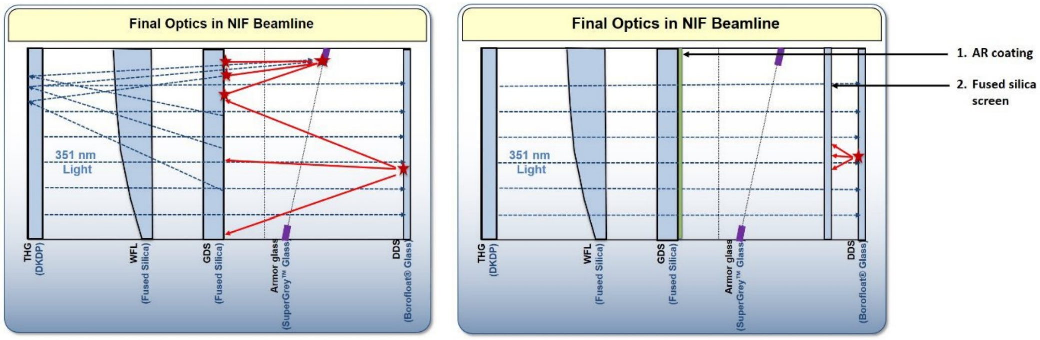


Figure 4-11: *Left*:A schematic representing the final optics in the NIF beamline showing the concept of surface bulk eruptions (red stars and red arrows) during shot operations migrating to the GDS optic with no FSDS optic installed. *Right*:A schematic showing the protection offered by installing an FSDS optic screen. An AR coating on the exit surface of the GDS also reduces reflected laser energy [3]

consideration as another potential implementation project to the NIF ORL System [11, 3, 15].

Implementing GDS AR coating technology into the NIF ORL System will extend the GDS coating and coating verification processes thus reducing the system's overall optic throughput. Since GDS optics are already typically coated on the input side, the system may already be fully equipped to coat the output side.

AMP Implementation Project

Prior to entering the NIF optics loop, new or refinished GDS and WFL optics are chemically treated in an Advanced Mitigation Process (AMP) to reduce the number of damage initiation sites that occur when optics are exposed to NIF's laser energies. The chemical treatment process conditions the optic surface microfractures making them less susceptible to laser-induced damage. Although fully deployed to condition new or refinished optics, AMP has yet to be added to the NIF ORL [24]. Researchers at the French Alternative Energies and Atomic Energy Commission (CEA) however have employed AMP processes within the Laser Megajoule (LMJ) optics recycle loop reporting improvements in damage threshold [4]. For this case study, we will consider adding an AMP process to the NIF ORL as a mature technology ready for implementation. Since NIF is already equipped for the AMP process, the primary impact to the recycle loop is the added processing times for both the GDS and WFL optics resulting in lower overall throughput.

4.4.2 Production Efficiency Initiatives

Some of the NIF ORL subsystems have been in service for over 20 years, initially tasked with producing the first set of final optics (well in the thousands) to fully populate the 192 beamlines of NIF. Some subsystems like the Optics Mitigation Facility (OMF) – a laser-based facility tasked with categorizing and physically reconditioning damage sites [6] – are prime candidates for technology infusion due to their operator-dependent manual operations and long process times. After over 20 years of service, other subsystems like the optics cleaning machines and metrology stations may now be experiencing much more downtime due to unplanned machine failures and faults triggered by the degradation of parts over time.

Automated OMF Project

When NIF laser-induced damage sites grow to unacceptable levels, GDS and WFL optics are removed from NIF and the sites are repaired using a laser-based material ablation system in the OMF. One by one, damage sites are located and evaluated using microscopes and high-resolution cameras by technicians to apply the appropriate protocols – typically matching the size of the conical repair geometry to each unique damage site - for repair. After determining the optimal conical size for each damage site, the system uses a CO_2 laser (as depicted in figure 4-12) to drill out damage site material to form conical features that are much less susceptible to laser-induced damage [6].

In 2017, NIF engineers developed machine-learning-based technology to automate the operator-dependent task of locating, evaluating, and categorizing damage sites to significantly reduce the amount of operator effort and OMF processing times. Although the OMF facility has already implemented this automation technology, we will consider this a potential project within this case study for the purpose of exploring its effect on the system [14].

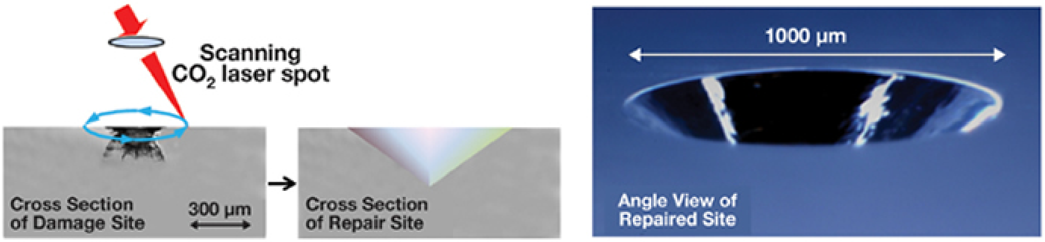


Figure 4-12: *Left*:A schematic depicting the CO_2 scanning pattern to ablate material to form conical repair sites. *Right*:A photo of the conical repair site [14].

High-speed OMF Stages

OMF processing speed is limited by the time required to analyze and mitigate each damage site. One limiting factor in improving processing speed can be stage motion technology. The OMF system architecture relies on a dual-axis optic traversing stage (shown in figure 4-13) [6]. Stage motion is required for repair of each damage site and an upgrade of the stage systems to those with higher speed capabilities can lead to significant process time savings. Upgrading the stage systems will require significant project capital expenditures and development effort but may be a more economical throughput-increasing option as opposed to scaling to add additional OMF stations.

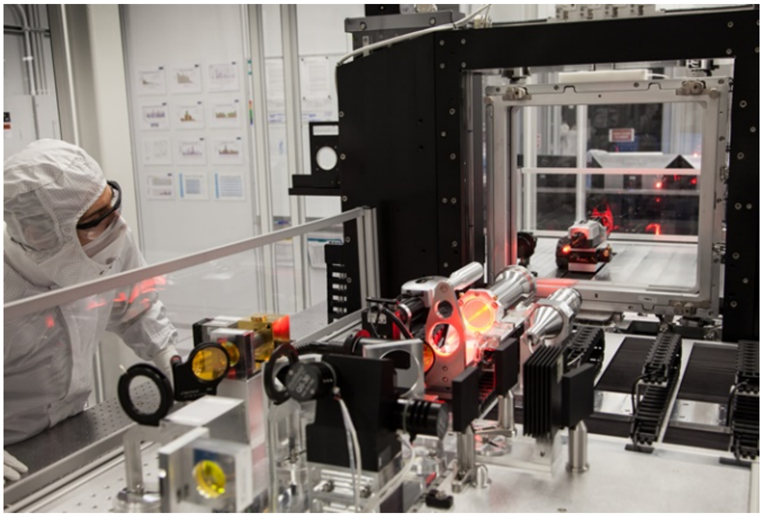


Figure 4-13: A photo taken in the Optics Mitigation Facility showing an operator observing optic mitigation processing [14]

Automated Metrology

To characterize and identify optic surface flaws in general, automated metrology stations (as shown in figure 4-14) largely rely on operator-dependent tasks. Operators use high-resolution cameras and microscopes to scan optical surfaces for flaws to record optic condition and to measure the effectiveness of the optics recycle effort [24]. This process may be significantly streamlined with machine learning technologies similar to those implemented in the OMF stations. Due to its potential for process time savings leading to higher overall ORL throughput and proven implementation of machine learning technology to similar systems, automating the metrology process will be considered a mature, potential implementation project for this case study.

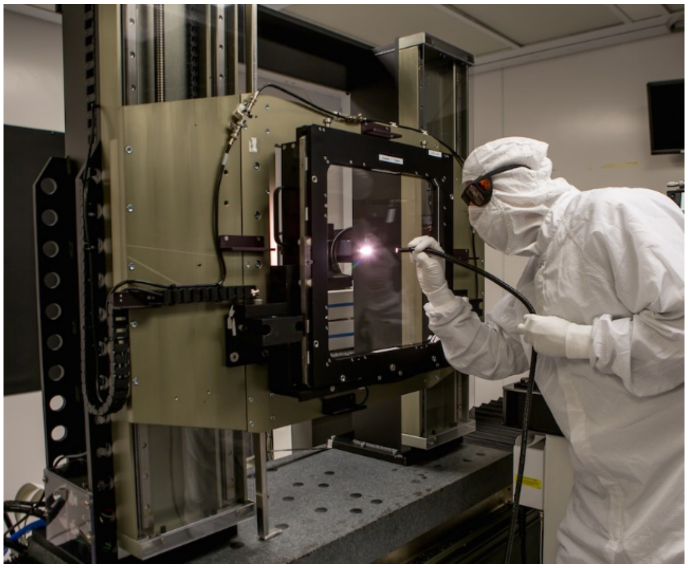


Figure 4-14: A photo taken in a NIF metrology facility showing an operator visually inspecting an optic suspended on a stage system [12]

Station Reliability Upgrades

Machine reliability issues can significantly reduce a processing station's availability resulting in lower overall product throughput. Typically, when machines malfunction, operators suspend processing while a team of engineers and technicians resolve the issues. The underlying causes of these issues include degradation of components over time, and low machine repeatability (inherent to the original design) leading to intermittent faults. Processing stations that exhibit consistent machine malfunctions are good candidates for reliability upgrade projects with a value proposition that significantly raises the station's availability.

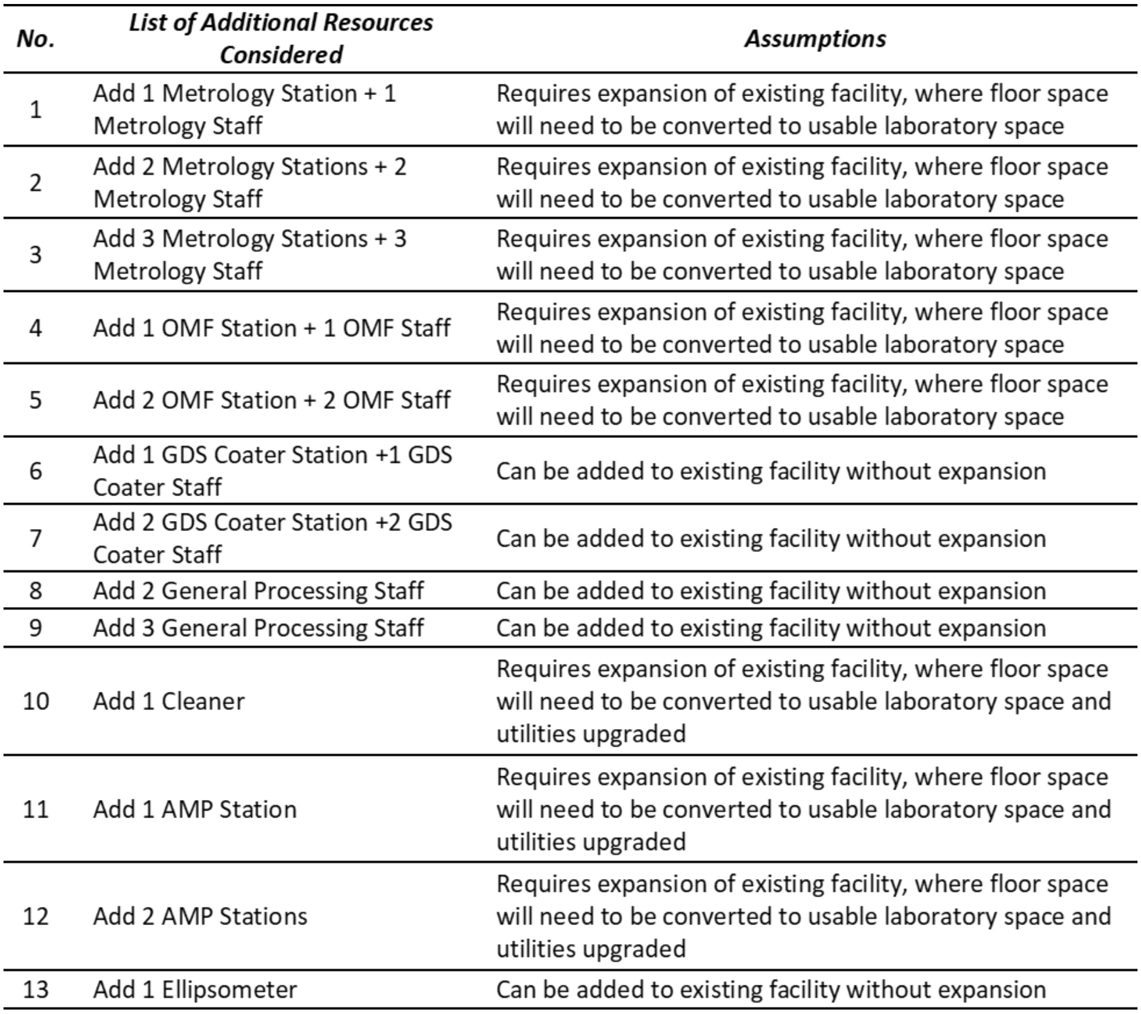
For this case study, we will assume that the cleaning stations and metrology stations routinely malfunction leading to significant unplanned downtime. We will also assume that the machines can be upgraded with mature, established technology to significantly improve station uptime as a potential implementation project.

4.4.3 DES-guided Scaling Projects

Adding more resources where needed in the process flow to alleviate bottlenecks is a great way to improve product throughput. Discrete Event Simulation (DES) results can be used to optimally guide the selection of bottleneck-alleviating projects to add staff and/or additional equipment incrementally only where needed. While scaling up to add staff and equipment leads to increased throughput, doing so may trigger a number of infrastructure challenges including: limited facility floor space, limited utility resources (electrical power, water, compressed air, HVAC systems, cleanroom flow systems, etc.), and limited space for facility expansion. For this case study, we will assume that incremental scaling of the resources shown in table 4.4 is feasible and can be considered potential implementation projects.

4.5 Step 4: Build a Production Throughput Model

The NIF ORL system is well-described in several journals, conference papers, and in LLNL produced media highlighting the system. Explicit process steps, process times, and machine reliability data however are not all readily available within the published works. Therefore, for this case study, we will make assumptions where needed to fill in boundary conditions needed for the simulation.



No.	*List of Additional Resources Considered*	*Assumptions*
1	Add 1 Metrology Station + 1 Metrology Staff	Requires expansion of existing facility, where floor space will need to be converted to usable laboratory space
2	Add 2 Metrology Stations + 2 Metrology Staff	Requires expansion of existing facility, where floor space will need to be converted to usable laboratory space
3	Add 3 Metrology Stations + 3 Metrology Staff	Requires expansion of existing facility, where floor space will need to be converted to usable laboratory space
4	Add 1 OMF Station + 1 OMF Staff	Requires expansion of existing facility, where floor space will need to be converted to usable laboratory space
5	Add 2 OMF Station + 2 OMF Staff	Requires expansion of existing facility, where floor space will need to be converted to usable laboratory space
6	Add 1 GDS Coater Station +1 GDS Coater Staff	Can be added to existing facility without expansion
7	Add 2 GDS Coater Station +2 GDS Coater Staff	Can be added to existing facility without expansion
8	Add 2 General Processing Staff	Can be added to existing facility without expansion
9	Add 3 General Processing Staff	Can be added to existing facility without expansion
10	Add 1 Cleaner	Requires expansion of existing facility, where floor space will need to be converted to usable laboratory space and utilities upgraded
11	Add 1 AMP Station	Requires expansion of existing facility, where floor space will need to be converted to usable laboratory space and utilities upgraded
12	Add 2 AMP Stations	Requires expansion of existing facility, where floor space will need to be converted to usable laboratory space and utilities upgraded
13	Add 1 Ellipsometer	Can be added to existing facility without expansion

Table 4.4: A list of all the incremental resource scaling project options considered and their assumed impact to the facility

4.5.1 Collect Production Data

The production process flows for both the GDS and WFL optics, shown in figure 4-15, begin when they are removed from NIF due to excessive damage site growth. The GDS optics are downstream (with respect to light flow) of the WFL optics and tend to damage at a much higher rate according to NIF researchers [2]. Therefore, we will assume for simplicity that the incoming optics for recycling enter the system at a rate of about 2 GDS optics for every 1 WFL optic. Due to the lack of published detailed production data, the data presented in this section are assumed and are presented for the purpose of demonstrating the production throughput model build process within this case study.

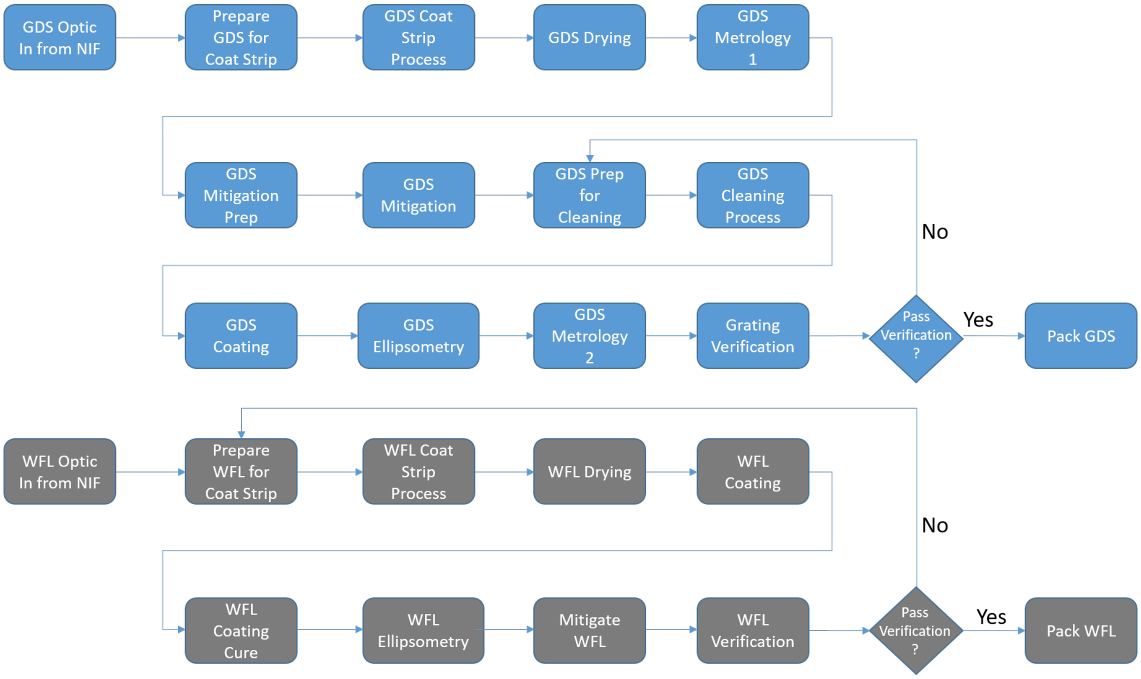


Figure 4-15: A flowchart depicting the NIF Optics Recycle Loop with abstracted processes for simplicity for both the GDS and WFL optics [24, 10]

The GDS recycle process begins when GDS optics are removed from NIF as Line Replaceable Units (LRUs) - optics assembled in mounting frames that interface to the NIF laser - and installed into cases for transport to the Optics Production Facility (OPF). When the GDS optics arrive, operators prepare them for stripping of the existing AR coatings by extracting the LRUs first from the cases and then the optics from the LRUs. The bare optics are then assembled to handling frames and placed in automated cleaning stations where the AR coating is stripped from the optic using aqueous solutions. After precision cleaning with deionized water, the optics are then inspected at a metrology station for flaw identification and characterization to fully map damage sites in need of mitigation repair. The optics are then transported to the OMF facility where each damage site undergoes localized repair using a CO_2 laser to ablate material, forming the conical mitigated sites. After mitigation repair, the optics are transported back to the OPF for cleaning and then application of a new AR coating. The new coating is then evaluated by an ellipsometer station prior to another trip to the metrology station to verify that damage sites have been properly repaired and that the optic did not sustain any process-induced damage. Throughout the recycle process, operators must carefully handle the optics since the slightest mishandling can lead to damage to the otherwise pristine optical surfaces. Finally, the GDS optic's grating performance is verified prior to packing the ready-to-use optics for storage [24, 10].

The WFL recycle process is similar but does not follow the same process steps and processing times due to its optical functionality as a focusing lens (as opposed to a diffractive optic like the GDS) and its off-axis curvature. WFL processing draws from the same staff resource pool, but some equipment resources are WFL-specific.

The first step in the GDS recycle loop - *Prepare GDS for Coat Strip*, as shown in figure 4-15 - will be explored in detail to highlight the production data needed for each process. This process begins when GDS optics arrive as assembled LRUs housed in transport cases and need to be prepared for the AR coating strip process. This preparation process involves:

- Removal of the LRUs from the transport cases
- Removal of the optics from the LRUs
- Assembly of optics to handling frames to interface to the cleaning machines

The resources required to perform this process include:

- General facility staff personnel (1)
- An optic load station
- A cleaning frame assembly station

Processing time variation is estimated as a 40, 50, 60-minute triangular distribution (min., mode, max.) and is attributed to two key factors: operator efficiency and the part-dependent ease of assembly. The general facility staff tasked with this work consists of several team members and processing speed is staff member dependent. Some optics can also be more difficult to disassemble than others due to hardware inconsistencies, therefore, requiring more process times than others. The estimated distribution is determined by collecting and analyzing process time datasets like the example shown in figure 4-16.

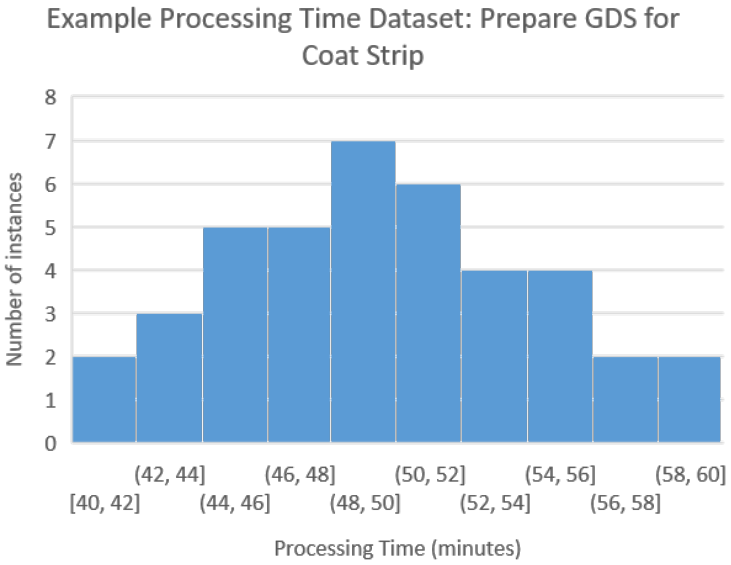


Figure 4-16: A histogram showing processing time data collected representing the *Prepare GDS for Coat Strip* process as an example

Machine and equipment upkeep in the form of planned preventative maintenance and unplanned malfunctions can have a profound impact on product throughput and operating costs (spare parts and staff effort) for the NIF ORL system. Due to the lack of published available machine maintenance and repair records, we will consider a scenario where 2 key stations – the cleaning stations and the metrology stations

– require routine preventative maintenance and consistently exhibit unplanned malfunction events that lead to significant downtime. This scenario assumes that analysis of maintenance logs for these machines reveal the following major event and downtime distribution trends:

- Cleaning machine preventative maintenance every 25 cycles with a triangularly distributed downtime of 7, 8, 9 hours (min., mode, max.)
- Cleaning machine major malfunction or fault events occurring about every 6 days with a triangularly distributed downtime of 8, 10, 12 hours (min., mode, max.)
- Metrology station major malfunction or fault events occurring about every 4 days with a triangularly distributed downtime of 10, 11, 12 hours (min., mode, max.)

4.5.2 Baseline Discrete Event Simulation

Now that we have gathered key production data, we can create a baseline discrete event simulation model that represents the NIF ORL system to better understand the relationship between project implementation decisions and product throughput in terms of the rate of GDS and WFL optics processed. The baseline simulation model represents the envisioned current NIF ORL system and serves as the initial system configuration. Rockwell Automation Technologies' Arena DES software was selected as a user-friendly package that considers all the prevalent throughput-contributing factors from the NIF ORL and provides automated post-processing reports containing key metrics and strong visuals to help locate process flow bottlenecks.

To build the DES model, the NIF ORL process flow diagrams for both the GDS and WFL optics (figure 4-16) were reconstructed within the Arena project workspace as shown in figure 4-17. *Create Modules* are the starting points for each optic flow simulation and set the rate of incoming parts or "entities" that enter the production system. For this baseline model, we have 2 entities that flow into individual flow paths set at a rate of 1 GDS optic every 4 hours and 1 WFL optic every 8 hours (mean times with random exponential distribution) to reflect the 2 to 1 GDS to WFL ratio of actual incoming optics pulled from NIF for recycling. Each of the subsequent process steps was created using *Process Modules* where the process times, statistical distributions, and resources needed are entered. Although two process flow paths (one for GDS and one for WFL) were created, the processes within the paths share many of the same resources – stations and their specialized equipment and station operators. Table 4.5 lists the shared equipment assumptions for the simulation model.

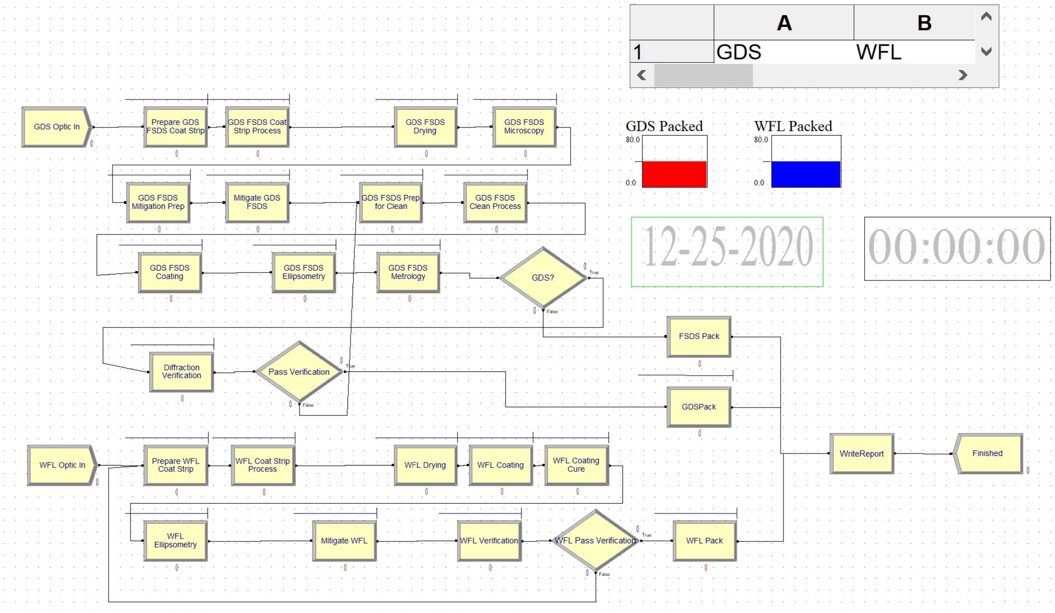


Figure 4-17: A screenshot of the Arena DES software workspace used to build model process flow

To prepare for the eventual exploration of the potential implementation projects described in sections 4.4.1 and 4.4.2, the model (shown in figure 4-18) was expanded to include considerations for processing FSDS optics in addition to GDSs and WFLs and the addition of AMP processes. An additional entity *Create Module* was added to represent FSDS optics flowing into the GDS process flow. The FSDS optic appears to be of similar size and shape as the GDS optic. Therefore, we will assume that it can be processed in a similar fashion. Since the FSDS does not function as a diffractive grating, a *Decide* module is used to filter out FSDS optic entities after the *GDS*

FSDS Metrology to send them to the *FSDS Pack* process instead of the *Diffraction Verification* process. Since these model expansions should not be considered for the baseline model, they are strategically set to parameters (such as zero AMP process times and zero incoming FSDS optics) to ensure they offer no effect on the system's throughput.

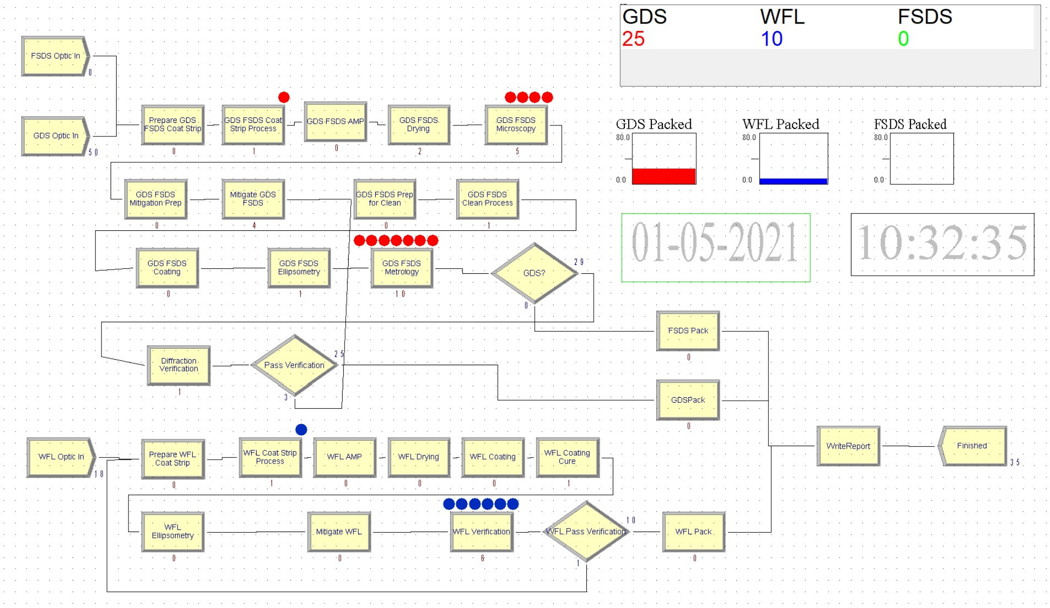
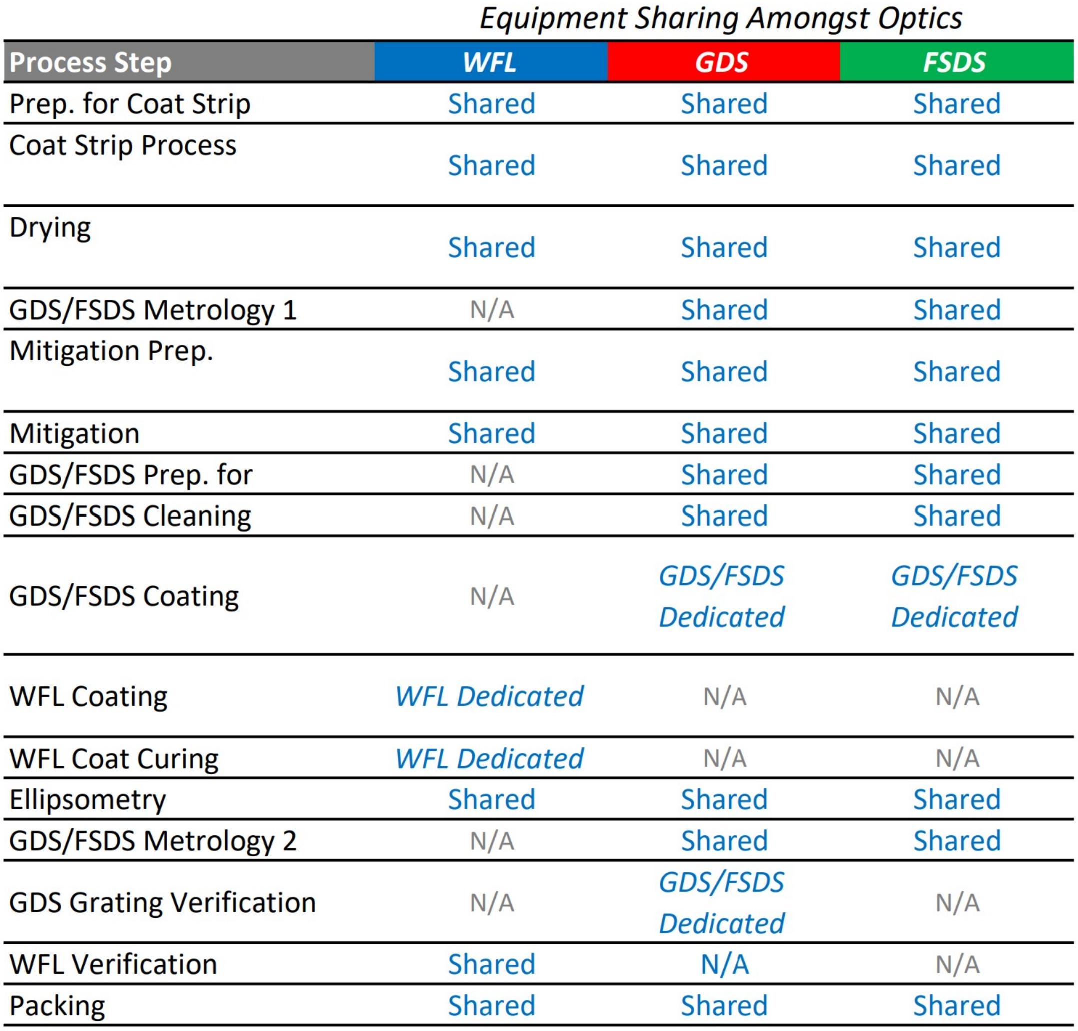


Figure 4-18: A screenshot of the Arena DES software workspace with FSDS model entities

Resource sets were created for multiple resources such as the four mitigation stations shown in figure 4-19 to allow the simulation to draw from a pool of resources instead of waiting for one specific machine, equipment, or operator. The simulation model can be visualized as 5 major stations operated by the 10 total staff positions as shown in figure 4-19. Optics flow from station to station, seizing and releasing equipment, machines, and staff. The 10 total staff positions are grouped into the following sets:

- 3 general staff positions operate the 2 cleaning stations, multiple drying carts, 1 GDS coat station, 2 WFL coat stations, and 1 WFL cure station
- 2 staff positions operate the 2 metrology stations
- 4 staff positions operate the 4 mitigation stations



Equipment Sharing Amongst Optics

Process Step	*WFL*	*GDS*	*FSDS*
Prep. for Coat Strip	Shared	Shared	Shared
Coat Strip Process	Shared	Shared	Shared
Drying	Shared	Shared	Shared
GDS/FSDS Metrology 1	N/A	Shared	Shared
Mitigation Prep.	Shared	Shared	Shared
Mitigation	Shared	Shared	Shared
GDS/FSDS Prep. for	N/A	Shared	Shared
GDS/FSDS Cleaning	N/A	Shared	Shared
GDS/FSDS Coating	N/A	*GDS/FSDS Dedicated*	*GDS/FSDS Dedicated*
WFL Coating	*WFL Dedicated*	N/A	N/A
WFL Coat Curing	*WFL Dedicated*	N/A	N/A
Ellipsometry	Shared	Shared	Shared
GDS/FSDS Metrology 2	N/A	Shared	Shared
GDS Grating Verification	N/A	*GDS/FSDS Dedicated*	N/A
WFL Verification	Shared	N/A	N/A
Packing	Shared	Shared	Shared

Table 4.5: A list of shared equipment amongst optics for each process step [24, 10]

- 1 staff position operates the 1 GDS diffraction verification station

The model is configured to allow processing when all resources for a particular process are available and to wait and create a queue when any of the required resources are unavailable. If for example, all drying carts are seized by the *GDS Drying* or *WFL Drying* process, the next optic ready for either drying process will wait in the process queue until the carts are made available.

Since machines and equipment can also be unavailable due to service or repair, the maintenance cycles and forecasted malfunction events are simulated in the model as well. For each equipment or machine resource, *Failures* (a feature within the Arena Software) can be added to represent scheduled maintenance and unplanned malfunctions and faults.

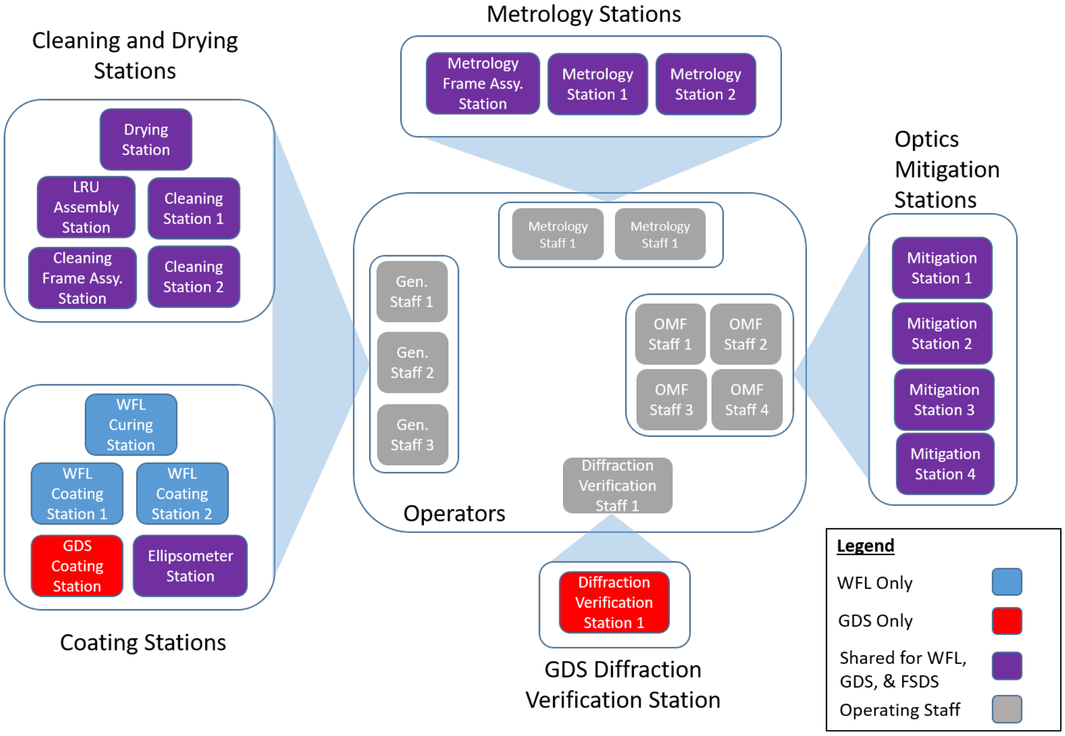


Figure 4-19: A schematic depicting the resources assumed for the DES baseline model

After inputting process details (GDS and WFL recycle flow processes, process times, resources, and maintenance downtime), simulation run parameters were added to represent the production schedule, the simulation run duration, and the total number of run replications. For the baseline simulation, the production schedule is assumed to be two shifts for a total of 16 work hours per day, 7 days a week. The length of the simulation was set to 30 days so the results represent monthly rates and the number of replications was set to 5 to gain data distribution insights while minimizing simulation run times.

Baseline Discrete Event Simulation Results and Model Verification

When running the simulation, the Arena software provides real-time entity progress tracking capabilities such as the number of entities (GDS, WFL, or Fused Silica Debris Shields [FSDS]) queued at processes, and the number of entities completed using visuals displayed in the workspace. During a simulation run (as shown in figure 4-18), red and blue filled circles represent GDS and WFL optics respectively, and appear when process resources are unavailable and the optics are waiting in process queues. The dashboard on the right provides real-time processing information such as the number of parts completed and the time and date progress of the 30-day run.

The baseline simulation ran successfully with a total average optic throughput of 82 GDS optics and 47 WFL optics for a total average throughput of 129 optics over a 30-day simulation period. In 2015, NIF researchers reported a recycle rate as high as 40 optics/week [24]. If we assume that the rate reported is a maximum weekly throughput under optimal conditions with actual weekly means of 32 optics/week, then our baseline simulation result rate of 129 optics/month is a reasonable representation of the NIF ORL rate of processing.

In addition to the product output results, the Arena built-in post-processing capabilities provide a detailed report with an extensive list of simulation run details such as:

- Entity processing (value-added) and wait times (non-value-added)
- Process queuing times and the average number of entities waiting to be processed
- Resource utilization ratio (time seized/time scheduled) and the number of times seized for use

Both the process queue time data and the resource utilization data within the report provide clues to better understand the model's throughput-limiting process bottlenecks and their oversubscribed resources. An examination of both the collection of red and blue queue indicators (figure 4-18) and the queue summary (table 4.6) show disproportionate queuing at the GDS/FDSD metrology processes and the WFL verification process. Since all 3 processes require the metrology station and their operators, it is not surprising that both metrology stations and their 2 operators are operating at .78 utilization. Although the operators can be further utilized to reach a maximum of 1.0 utilization, the metrology stations have reached their maximum utilization due to maintenance and repair downtime considerations occupying the remaining .12 utilization. Based on the queue wait time and resource utilization results, we can identify the throughout-limiting process and resources. For the baseline model, it is clear that optics throughput can be improved with the addition of metrology stations.

4.5.3 Exploring the Project Selection Space

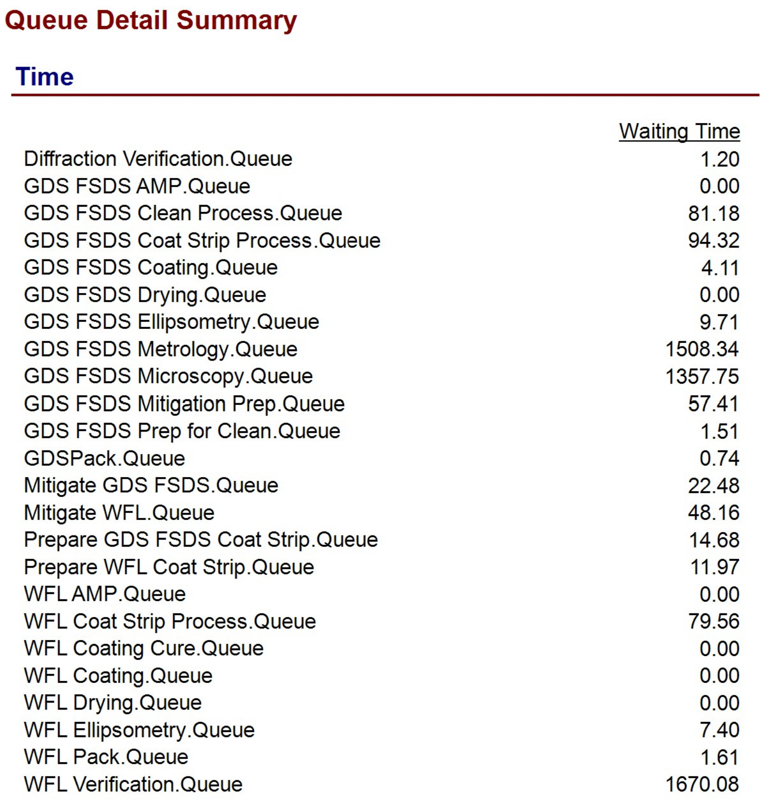
Now that we have established a baseline DES model verified by comparing the model optics throughput rate to the published NIF ORL's optic throughput rate, we can explore the model's response to changes representing the product improvement, efficiency improvement, and the DES-guided scaling projects described in section 4.4.3. The strategy to fully explore this project selection space is to:

1. Explore the 7 model scenarios that represent each of the 7 potential product and efficiency improvement projects to better understand sensitivities

2. Explore the 13 model scenarios that represent each of the 13 potential scaling projects to better understand sensitivities

3. Explore scenarios representing combinations of the 7 potential product and efficiency improvement projects

4. Further explore each combination scenario using DES-guided scaling in a One-



Queue Detail Summary

Time

	Waiting Time
Diffraction Verification.Queue	1.20
GDS FSDS AMP.Queue	0.00
GDS FSDS Clean Process.Queue	81.18
GDS FSDS Coat Strip Process.Queue	94.32
GDS FSDS Coating.Queue	4.11
GDS FSDS Drying.Queue	0.00
GDS FSDS Ellipsometry.Queue	9.71
GDS FSDS Metrology.Queue	1508.34
GDS FSDS Microscopy.Queue	1357.75
GDS FSDS Mitigation Prep.Queue	57.41
GDS FSDS Prep for Clean.Queue	1.51
GDSPack.Queue	0.74
Mitigate GDS FSDS.Queue	22.48
Mitigate WFL.Queue	48.16
Prepare GDS FSDS Coat Strip.Queue	14.68
Prepare WFL Coat Strip.Queue	11.97
WFL AMP.Queue	0.00
WFL Coat Strip Process.Queue	79.56
WFL Coating Cure.Queue	0.00
WFL Coating.Queue	0.00
WFL Drying.Queue	0.00
WFL Ellipsometry.Queue	7.40
WFL Pack.Queue	1.61
WFL Verification.Queue	1670.08

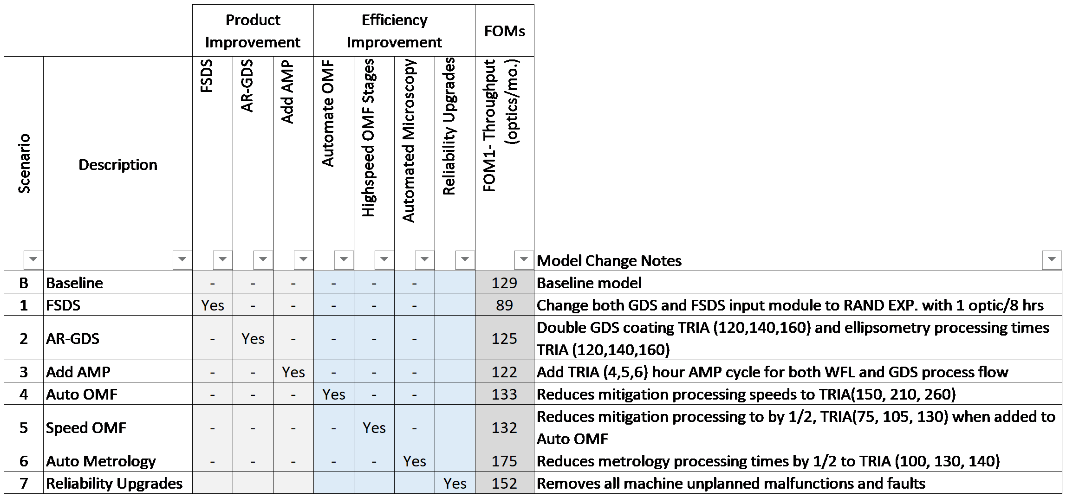
Table 4.6: A list of resource queue times output from the Arena DES model displaying 30-day total wait times in minutes

Factor-At-a-Time (OFAT) manner to incrementally add the 13 potential scaling projects to increase optics throughput

Simulating and Running 7 Initial Scenarios

Each of the scenarios (1-7) shown in table 4.7 represent the addition of a single product or efficiency project to the system configuration considered to be our baseline as described in section 4.5.2. Simulating each of these scenarios in Arena allows for a better understanding of system sensitivity in terms of optics throughput in response to these projects individually. Scenarios 1-3 represent the three product improvement projects that improve the optic damage threshold (FOM1) but place a greater demand on the NIF ORL system, thus reducing its optic throughput. Scenarios 4-7 represent the four efficiency improvement projects that have no effect on the optics damage threshold but may improve optics throughput by reducing processing times and machine downtimes.

Scenario 1 - FSDS represents the scenario where the FSDS optic technology is added to the NIF ORL as an implementation project. The addition of the FSDS optic is considered a product improvement project since its value proposition is forecasted to improve the damage threshold (J/cm^2). This improvement however places a new demand on the NIF ORL system to process FSDS optics in addition to GDS optics and WFL optics and should significantly reduce GDS and WFL optic throughput. As described in section 4.5.2, an inactive FSDS optic entity *Create* module was added to the baseline model. To simulate this scenario, the FSDS input module is activated within the model to input 1 FSDS optic every 8 hours. The GDS input module rate is reduced to 1 GDS optic every 8 hours (baseline is 1 optic every 4 hours). The FSDS recycle rate is assumed to be proportional to the GDS and WFL rates since it is added to help offset some of the damage incurred. The model also assumes that the FSDS requires similar cleaning, coating, and mitigation processes to the GDS, but does not require diffraction verification as it functions as a transmissive debris shield and not as a diffractive optic. As expected, the addition of FSDS optic processing to the NIF ORL comes at a significant throughput cost as simulation results indicate that throughout drops from 129 (table 4.7 – Scenario B) to only 89 optics per month. It should be noted that only GDS and WFL optics processed are counted (processed FSDS optics are not counted) for comparison purposes due to scenarios that do not include the FSDS project and thus do not produce FSDS optics.



		Product Improvement			Efficiency Improvement				FOMs	
Scenario	Description	FSDS	AR-GDS	Add AMP	Automate OMF	Highspeed OMF Stages	Automated Microscopy	Reliability Upgrades	FOM1- Throughput (optics/mo.)	Model Change Notes
B	Baseline	-	-	-	-	-	-		129	Baseline model
1	FSDS	Yes	-	-	-	-	-		89	Change both GDS and FSDS input module to RAND EXP. with 1 optic/8 hrs
2	AR-GDS	-	Yes	-	-	-	-		125	Double GDS coating TRIA (120,140,160) and ellipsometry processing times TRIA (120,140,160)
3	Add AMP	-	-	Yes	-	-	-		122	Add TRIA (4,5,6) hour AMP cycle for both WFL and GDS process flow
4	Auto OMF	-	-	-	Yes	-	-		133	Reduces mitigation processing speeds to TRIA(150, 210, 260)
5	Speed OMF	-	-	-	-	Yes	-		132	Reduces mitigation processing to by 1/2, TRIA(75, 105, 130) when added to Auto OMF
6	Auto Metrology	-	-	-	-	-	Yes		175	Reduces metrology processing times by 1/2 to TRIA (100, 130, 140)
7	Reliability Upgrades							Yes	152	Removes all machine unplanned malfunctions and faults

Table 4.7: A scenario list consisting of the baseline scenario and 7 scenarios representing each product and efficiency improvement projects

Scenario 2 – AR-GDS represents the scenario where the GDS optic's output surface containing the diffractive grating is coated in addition to its input surface as an implementation project. This scenario is forecasted to improve optics damage threshold as well by allowing more laser energy to pass through the optic towards the NIF target and by minimizing optic-damaging output surface reflections. Implementing this will however extend the GDS coating and ellipsometry-based coating inspection processes, perhaps reducing optic throughput. To represent this in a simulation model, the baseline model's GDS coating and inspection process times were doubled, based on the assumption that coating 2 sides instead of 1 requires approximately 2 times the processing time. The simulation results indicate that this project reduces the overall optic throughput from 129 to 125 optics per month. This marginal decrease is expected since slightly longer overall process times will lead to slightly reduced throughput and the GDS coating process does not appear to be the baseline model's process bottleneck.

Scenario 3 – Add AMP represents the scenario where an AMP process (chemical treatment process) is added to improve the optics damage threshold (J/cm^2) as an implementation project. This process is already deployed for new optics but we will assume that adding it to the NIF ORL process is beneficial as well. To simulate this scenario, the baseline model's GDS/FSDS AMP and *WFL AMP* process modules were activated assuming a triangular process distribution with a mode time of 5 hours (4 hours min. and 6 hours max.). The simulation results indicate that this project reduces the overall optic throughput from 129 to 122 optics per month. Again, this decrease in throughput is expected due to the increase in the overall process times.

Scenario 4 – Auto OMF represents the scenario where the optic mitigation process is streamlined with machine learning technology and added to the NIF ORL as an implementation project. This project does not improve product performance but significantly reduces the mitigation process times. To simulate this scenario, the baseline model mitigation assumption of a triangular distribution with a mode of 500 minutes (350 min. 650 max.) was reduced to a mode of 210 minutes (150 min. and 260 max.). The simulation results indicate that this project increases the overall optic throughput from 129 to 133, which is expected due to the overall process time decrease.

Scenario 5 – Speed OMF represents the scenario where the optic migration stations are upgraded with the latest motion control technologies to significantly increase the machine speed for damage site repair. This implementation project does not improve product performance but is assumed to reduce mitigation process times by a factor of 2. To simulate this scenario, the baseline model mitigation process times are therefore reduced by a factor of 2. As expected, the simulation results indicate that this project increases the optic throughput from 129 to 132 due to the reduced overall process time.

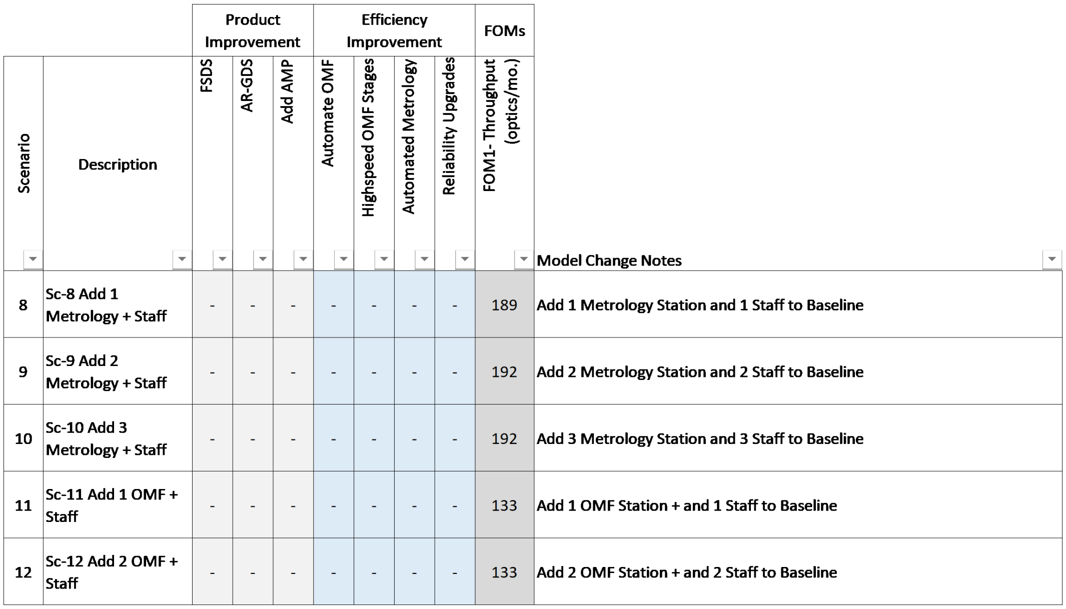
Scenario 6 – Auto Metrology represents the scenario where the metrology stations are upgraded with machine learning technology to automate the metrology processes. This implementation project does not improve product performance but is assumed to reduce metrology process times by a factor of 2. To simulate this scenario, the baseline model metrology process times are therefore reduced by a factor of 2. The simulation results indicate that this project increases the optic throughput significantly from 129 to 175. This significant increase is expected since the three metrology processes were identified in the baseline model as having the longest queue times. A reduction in metrology process times significantly increases the flow through these processes thus increasing optics throughput.

Scenario 7 – Reliability Upgrades represents the scenario where the cleaning stations and the metrology stations are upgraded to eliminate unplanned machine malfunctions and faults that lead to significant station downtime. This implementation project does not improve product performance but is assumed to increase the availability of the cleaning stations and the metrology stations. To simulate this scenario, the baseline model's cleaning station and metrology station's unplanned malfunction and faults are removed. The simulation results indicate that this project increases the optic throughput significantly from 129 to 152. This significant increase is expected since we have already identified the three metrology processes as process bottlenecks. Any reduction in metrology process times (as represented in Scenario 6) or increase in metrology station availability – as represented in this scenario - will result in profound throughput improvements.

Simulating and Running OFAT Scaling Scenarios

To further study the simulation model sensitivities to potential implementation projects, each scaling project, described in section 4.4.3, was modeled and simulated. Scenarios 8 through 20 (shown in table 4.8 as a partial list and in table A.1 as a full list) explore the optics throughput response to model changes representing the 13 potential scaling projects. Resource quantity changes were made to represent each scenario. As expected, adding metrology station resources as depicted in scenarios 8, 9, and 10, significantly clears the process flow bottleneck resulting in simulated optics throughput increases from 129 (baseline) to 189, 192, and 192 per month respectively. The minimal increases however in throughput in scenarios 9 and 10 (192 optics/month each) when compared to scenario 8 (189 optics/month) suggest that only 1 additional metrology station and station operator are needed to clear the baseline model's metrology bottleneck and any additional metrology resources (depicted in scenarios 9 and 10) provide minimal throughput benefit to the system.

Simulation runs for scenarios 11 – 20 resulted in minimal optics throughput changes. Predictably, scenarios that added both station and staff resources resulted in slight increases in optics throughput. Interestingly, scenarios 17-19 resulted in slight decreases in optics throughput. Although a bit counter-intuitive, these scenarios actually decrease in throughput since staff resources were not added creating a simulation condition where operators are oversubscribed by manning multiple stations.



		Product Improvement			Efficiency Improvement				FOMs	
Scenario	Description	FSDS	AR-GDS	Add AMP	Automate OMF	Highspeed OMF Stages	Automated Metrology	Reliability Upgrades	FOM1- Throughput (optics/mo.)	Model Change Notes
8	Sc-8 Add 1 Metrology + Staff	-	-	-	-	-	-	-	189	Add 1 Metrology Station and 1 Staff to Baseline
9	Sc-9 Add 2 Metrology + Staff	-	-	-	-	-	-	-	192	Add 2 Metrology Station and 2 Staff to Baseline
10	Sc-10 Add 3 Metrology + Staff	-	-	-	-	-	-	-	192	Add 3 Metrology Station and 3 Staff to Baseline
11	Sc-11 Add 1 OMF + Staff	-	-	-	-	-	-	-	133	Add 1 OMF Station + and 1 Staff to Baseline
12	Sc-12 Add 2 OMF + Staff	-	-	-	-	-	-	-	133	Add 2 OMF Station + and 2 Staff to Baseline

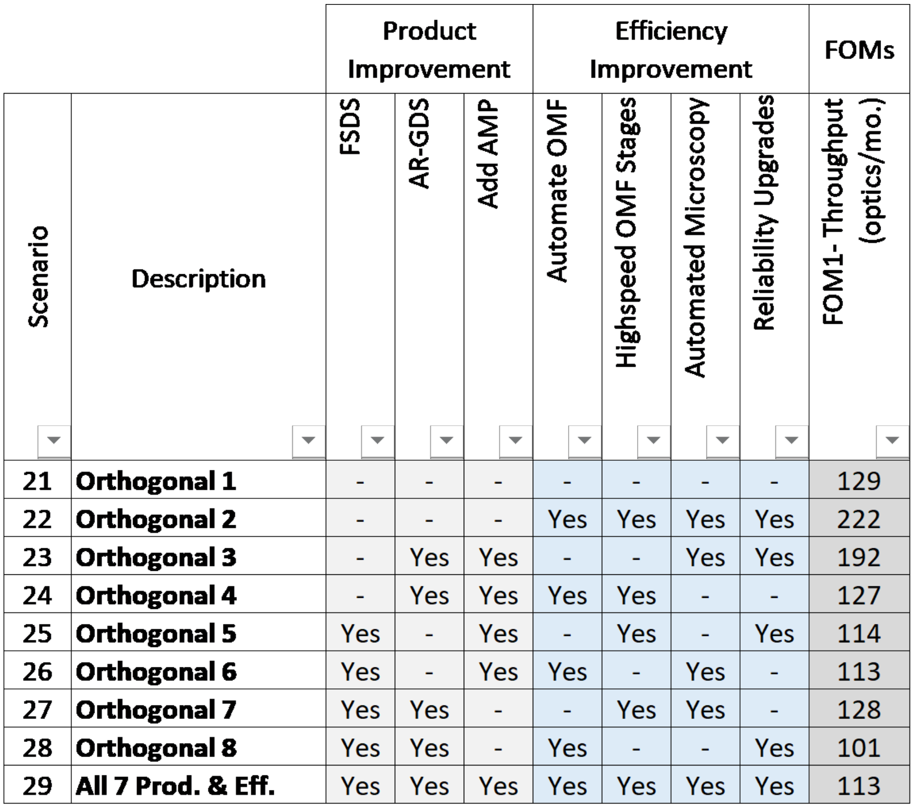
Table 4.8: A partial list of the DES-guided scaling scenarios representing each scaling project to study throughput sensitivity

Exploring Combined Project Scenarios

Ideally, all possible combinations of the 7 product improvement and efficiency improvement projects would be explored in the search for projects to include in the proposed project portfolio. Each of these 7 projects can be included or not included in each combined project scenario resulting in 128 possible combinations. Since each combination should also consider DES guided OFAT scaling projects added incrementally, the number of scenarios to explore can balloon to more than 500 unique scenarios to simulate. Although Arena's process analyzer tool allows some automated scenario exploration, it is largely limited to model changes that can be represented by simple parameter value changes. Since the baseline model requires more than parameter value changes to explore the full breadth of project options, exploration of 500 unique scenarios would require modeling and running each scenario simulation manually – an onerous and time-consuming proposition.

Instead, we can gain significant insight by using an L8, 2-factor, 7-level orthogonal array to explore the project option space and effectively manage the effort required. With this technique, 8 product performance and efficiency improvement project combinations are explored. The project combination where all 7 product performance and efficiency improvement projects are considered (Scenario 29) was also explored. Each of these 9 combinations was then further explored with numerous DES-guided incremental additions of the scaling projects for a total of 50 scenarios – a more reasonable set of models to build and run.

The 9 combined projects explored are shown in table 4.9 as scenarios 21 through 29. **Scenario 22 – Orthogonal 2** combines all the throughput-boosting efficiency improvement projects while excluding all the throughput-lowering product improvement projects, predictably resulting in the most significant throughput increase from 129 (baseline represented by scenario 21) to 222 optics per month. Interestingly, including all 7 product and efficiency improvement projects as **Scenario 29 – All 7 Prod. & Eff.** results in an overall decrease in throughput with simulation results of only 113 optics per month. We can surmise then that the combination of the product improvement projects has a profound impact on throughput that cannot be fully negated even with the entire combination of efficiency improvement projects. If all product improvement projects are indeed selected for implementation in the project portfolio, then scaling projects must be added to maintain the baseline throughput of 129 optics per month.



		Product Improvement			Efficiency Improvement				FOMs
Scenario	Description	FSDS	AR-GDS	Add AMP	Automate OMF	Highspeed OMF Stages	Automated Microscopy	Reliability Upgrades	FOM1- Throughput (optics/mo.)
21	**Orthogonal 1**	-	-	-	-	-	-	-	129
22	**Orthogonal 2**	-	-	-	Yes	Yes	Yes	Yes	222
23	**Orthogonal 3**	-	Yes	Yes	-	-	Yes	Yes	192
24	**Orthogonal 4**	-	Yes	Yes	Yes	Yes	-	-	127
25	**Orthogonal 5**	Yes	-	Yes	-	Yes	-	Yes	114
26	**Orthogonal 6**	Yes	-	Yes	Yes	-	Yes	-	113
27	**Orthogonal 7**	Yes	Yes	-	-	Yes	Yes	-	128
28	**Orthogonal 8**	Yes	Yes	-	Yes	-	-	Yes	101
29	**All 7 Prod. & Eff.**	Yes	Yes	Yes	Yes	Yes	Yes	Yes	113

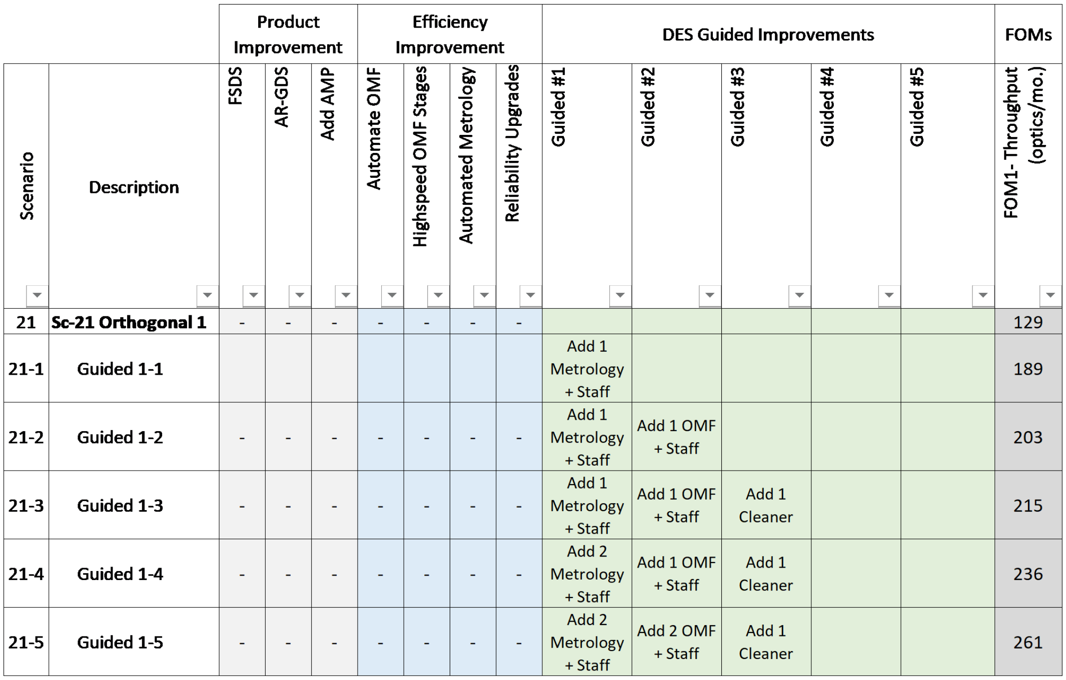
Table 4.9: A list of model scenarios 21-29 representing orthogonal array combinations of projects

Further Exploration Using DES-guided Scaling

To further explore scenarios 21-29, scaling projects were strategically added incrementally to improve optics throughput. Scenarios 21-1 through 21-5 shown in table 4.10 for example are DES-guided scenarios where each preceding scenario's simulation results are analyzed to identify the greatest resource needs (by examining queue times and resource utilization). The most impactful scaling project option was then added in the subsequent scenario, thus reducing bottleneck effects and increasing optic throughput. If we examine scenario 21-1, 1 metrology station and 1 metrology operator were added based on scenario 21's simulation results indicating long process queue times could be reduced with the addition of these two resources. Scenarios 21-2 through 21-5 then incrementally add 1 mitigation station and 1 mitigation operator, 1 cleaner, another metrology station and metrology operator, and finally, another mitigation station and mitigation operator. With each scaling project addition, the optics throughput increases as expected. Scaling projects are added incrementally and tracked as individual scenarios because they each represent options in the selection of the projects to fund within the project portfolio. A full list of the scenarios, their DES-guided incremental improvement projects added, and simulation results can be found in tables A.1, A.2, A.3, and A.4.

4.6 Step 5: Build a Product Performance Model

Since product performance is also highly valued, a model is needed to assess a scenario's optic damage threshold (FOM2). The underlying scientific principles of optics damage are not yet well-understood. Leading optics researchers like those at LMJ and NIF have theories of why damage sites initiate and grow and how they can be mitigated, but these theories are supported empirically with test data rather than with physics-based equations. Conservatively, we will assume the baseline scenario (B) to have a damage threshold of 4 $\mathrm{J/cm^2}$ based on published reports from NIF researchers [24]. Only three projects considered for the project portfolio – *FSDS*, *AR-GDS*, and *Add AMP* – are forecasted to improve on this FOM.



		Product Improvement			Efficiency Improvement				DES Guided Improvements					FOMs
Scenario	Description	FSDS	AR-GDS	Add AMP	Automate OMF	Highspeed OMF Stages	Automated Metrology	Reliability Upgrades	Guided #1	Guided #2	Guided #3	Guided #4	Guided #5	FOM1- Throughput (optics/mo.)
21	**Sc-21 Orthogonal 1**	-	-	-	-	-	-	-						129
21-1	Guided 1-1								Add 1 Metrology + Staff					189
21-2	Guided 1-2	-	-	-	-	-	-	-	Add 1 Metrology + Staff	Add 1 OMF + Staff				203
21-3	Guided 1-3	-	-	-	-	-	-	-	Add 1 Metrology + Staff	Add 1 OMF + Staff	Add 1 Cleaner			215
21-4	Guided 1-4	-	-	-	-	-	-	-	Add 2 Metrology + Staff	Add 1 OMF + Staff	Add 1 Cleaner			236
21-5	Guided 1-5	-	-	-	-	-	-	-	Add 2 Metrology + Staff	Add 2 OMF + Staff	Add 1 Cleaner			261

Table 4.10: A list containing scenario 21 and its 5 DES-guided sub-scenarios

Early reports from NIF researchers suggest that adding an FSDS to the NIF may reduce particle contamination on the GDS from shot operations [15, 3]. Reducing contamination increases the optic quality and therefore the optic's damage threshold. For this case study, we will conservatively assume that the inclusion of the *FSDS Project* provides a damage threshold increase by a factor of 1.3.

AR-GDS technology, according to published reports from NIF researchers, may also contribute to reducing shot-induced particle contamination on the GDS by reducing the reflected light energy absorbed by IOM components. NIF researchers suspect that reflected light energy interactions with glass armoring components (used to protect beam tube walls from stray reflections) contribute to particle generation and migration to the GDS [11, 3]. It appears that this technology provides a significant boost to damage threshold by improving optic quality that is attributed to reduced surface contamination. For this case study, we will assume that the inclusion of the *AR-GDS Project* provides a damage threshold increase by a factor of 1.3.

Researchers at CEA published LMJ optics recycle loop details that included an AMP process, suggesting optics performance benefits from this chemical treatment process [4]. Although the benefits of AMP processes are well-documented by NIF researchers, most of the published data only consider the AMP process to prepare new optics, but not as part of the recycle loop. Due to the limited data available, we will conservatively assume that the inclusion of the *Add AMP Project* provides a damage threshold increase by a factor of 1.1.

For a given scenario, the damage threshold ratio, D_{TR} is determined by:

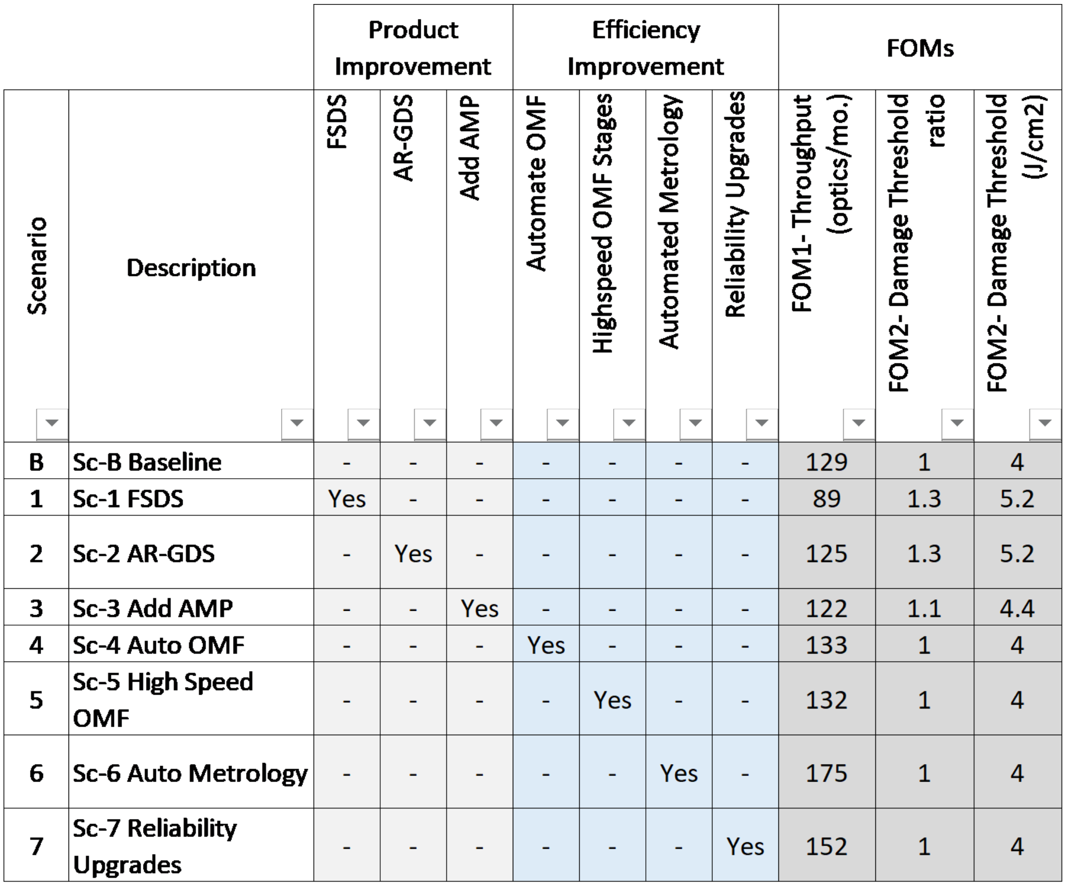
$$D_{TR} = F_{DF} * AR_{DF} * AMP_{DF}$$

Here, F_{DF} is the FSDS damage threshold factor (1.3 when the *FSDS Project* is selected, 1.0 when not selected), AR_{DF} is the AR-GDS damage threshold factor (1.3 when the *AR-GDS Project* is selected, 1.0 when not selected), and AMP_{DF} is the AMP damage threshold factor (1.1 when the *Add AMP Project* is selected, 1.0 when not selected).

Table 4.11 shows the assumed damage thresholds, and their ratios for scenario B through scenario 7. A full list is available in tables A.1, A.2, A.3, and A.4.

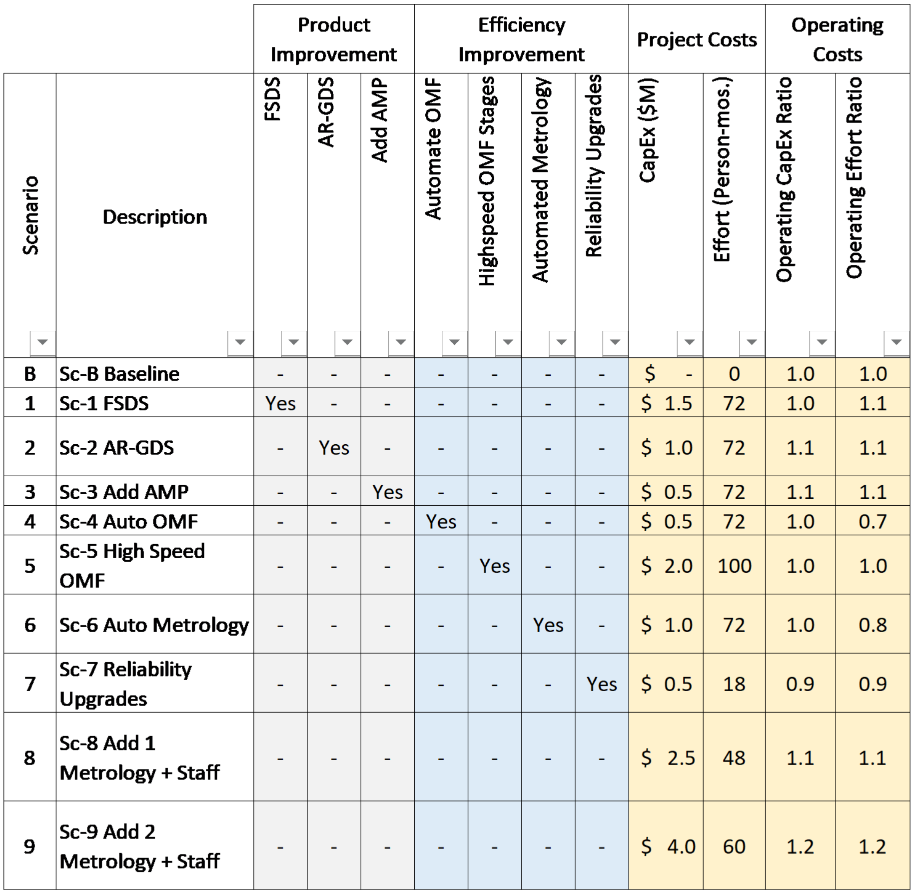
4.7 Step 6: Build a Cost Model

To properly assess the value of each of the scenarios considered, we must build a cost model to inevitably weigh the tradeoffs between the benefits of improved performance and their associated costs. Our stakeholders in this case study are most concerned with two cost categories: project costs and operating costs. Project costs include all estimated capital expenditures ($M) and staff effort (person-months) to develop, build, and commission equipment and processes. Operating costs include all estimated operations-related capital expenditures (such as spare parts, consumables, and maintenance equipment), and the staff effort needed to operate and maintain the system.



		Product Improvement			Efficiency Improvement				FOMs		
Scenario	Description	FSDS	AR-GDS	Add AMP	Automate OMF	Highspeed OMF Stages	Automated Metrology	Reliability Upgrades	FOM1- Throughput (optics/mo.)	FOM2- Damage Threshold ratio	FOM2- Damage Threshold (J/cm2)
B	Sc-B Baseline	-	-	-	-	-	-	-	129	1	4
1	Sc-1 FSDS	Yes	-	-	-	-	-	-	89	1.3	5.2
2	Sc-2 AR-GDS	-	Yes	-	-	-	-	-	125	1.3	5.2
3	Sc-3 Add AMP	-	-	Yes	-	-	-	-	122	1.1	4.4
4	Sc-4 Auto OMF	-	-	-	Yes	-	-	-	133	1	4
5	Sc-5 High Speed OMF	-	-	-	-	Yes	-	-	132	1	4
6	Sc-6 Auto Metrology	-	-	-	-	-	Yes	-	175	1	4
7	Sc-7 Reliability Upgrades	-	-	-	-	-	-	Yes	152	1	4

Table 4.11: A list containing the baseline scenario and scenarios 1-7 showing the optics damaged threshold values and ratios assumed



		Product Improvement			Efficiency Improvement				Project Costs		Operating Costs	
Scenario	Description	FSDS	AR-GDS	Add AMP	Automate OMF	Highspeed OMF Stages	Automated Metrology	Reliability Upgrades	CapEx ($M)	Effort (Person-mos.)	Operating CapEx Ratio	Operating Effort Ratio
B	Sc-B Baseline	-	-	-	-	-	-	-	$ -	0	1.0	1.0
1	Sc-1 FSDS	Yes	-	-	-	-	-	-	$ 1.5	72	1.0	1.1
2	Sc-2 AR-GDS	-	Yes	-	-	-	-	-	$ 1.0	72	1.1	1.1
3	Sc-3 Add AMP	-	-	Yes	-	-	-	-	$ 0.5	72	1.1	1.1
4	Sc-4 Auto OMF	-	-	-	Yes	-	-	-	$ 0.5	72	1.0	0.7
5	Sc-5 High Speed OMF	-	-	-	-	Yes	-	-	$ 2.0	100	1.0	1.0
6	Sc-6 Auto Metrology	-	-	-	-	-	Yes	-	$ 1.0	72	1.0	0.8
7	Sc-7 Reliability Upgrades	-	-	-	-	-	-	Yes	$ 0.5	18	0.9	0.9
8	Sc-8 Add 1 Metrology + Staff	-	-	-	-	-	-	-	$ 2.5	48	1.1	1.1
9	Sc-9 Add 2 Metrology + Staff	-	-	-	-	-	-	-	$ 4.0	60	1.2	1.2

Table 4.12: A list containing the baseline scenario and scenarios 1-9 showing assumed project and operating costs

4.7.1 Project Cost Model

To create a project cost model, each of three product improvement projects, four efficiency improvement projects, and 13 scaling projects were each assigned an estimated capital expenditure cost ($M) and staff effort (person-months) to include:

- Prototypes and test equipment procurements
- Off-the-shelf and fabricated component procurements
- Facility renovation procurement contracts
- Development, build, and commissioning effort

To determine the total project portfolio costs for each scenario, the individual costs (both capital expenditures and staff effort) for all projects selected are simply summed. Unfortunately, NIF project costs at this level are not readily available. Typically, similar legacy projects and equipment within the organization offer a good basis for cost estimates. We can however make reasonable estimates based on published process descriptions of the underlying technology and NIF produced media depicting the facilities, process equipment, and their quality standards.

Of the three product improvement projects (*FSDS*, *AR-GDS*, *Add AMP*), the *FSDS Project* has the potential to be the costliest in terms of capital expenditures. The project proposes the addition of a new optic to the existing NIF ORL system likely requiring the development of new optic handling hardware, new process procedures, and potential modifications to machines. Conversely, the *AR-GDS Project* appears to require additional GDS processing steps at existing machines already equipped to process the GDS optic. Similarly, the *Add AMP Project* may require minimal equipment development since the AMP process is already well-established at NIF. All 3 projects will likely require significant testing as well leading to additional capital expenditures and effort. For this case study, we will assume that selection of the *FSDS Project* will carry a capital expenditure of $1.5M, the *AR-GDS Project* will cost $1M, and the *Add AMP Project* will cost $0.5M. We will also assume that all three projects will require similar development effort at 72 person-months.

Of the four efficiency improvement projects (*Automate OMF*, *High-speed OMF Stages*, *Automated Metrology*, *Reliability Upgrades*) the *High-speed OMF Stage Project* appears to require the most capital expenditures to possibly procure new high-precision motion control systems and dual-axis stages. The *Automated OMF Project* may be very economical, possibly only requiring a new control system, new cameras, and new software to introduce machine learning technology [14]. The *Reliability Upgrade Project* may also be a more economical option where the most significant machine reliability issues are addressed with hardware upgrades. For this case study, we will assume that selection of the *Automate OMF Project* will carry a capital expenditure of \$0.5M, the *High-Speed OMF Stages Project* will cost \$2M, the *Automated Metrology Project* will cost \$1M, and the *Reliability Upgrade Project* will cost \$0.5M. We will also assume that the *High-speed OMF Stages Project* is forecasted as a 100 person-month effort, the two automation projects to be 72 person-month efforts each, and the *Reliability Upgrade Project* to be an 18 person-month effort.

The 13 scaling projects represent an expansion of the production facilities and can carry high capital expenditures since they may involve the procurement of multiple process machines and facility renovations. Facility renovations may also require the conversion of general-purpose space to science laboratory-grade cleanroom space. Scaling to add machines may also require various utility upgrades as well. For this case study, we will assume various capital expenditures for scaling projects ranging from \$1M to \$5.5M. We will also assume that the staff effort required ranges from 24 to 72 person-months. A partial list of the assumed project costs for this case study is shown in table 4.12 (a full list is available in tables A.1, A.2, A.3, and A.4)

4.7.2 Operating Cost Model

In contrast to the project cost model, the operating cost model employs factors to represent increases or decreases to the baseline operating costs. Each of the 3 product improvement projects, the 4 efficiency improvement projects and the 13 scaling projects were each assigned an estimated operating capital expenditure factor and a staff effort factor that consider:

- Consumable and spare part procurements
- Contracted machine repair and service procurements
- In-house machine upkeep effort (maintenance, repair, troubleshooting)
- Staffing effort (operators, maintenance, engineering staff)

Each factor assigned is meant to represent a relative increase or decrease to the baseline scenario considered to be the current state of the NIF ORL. As shown in table 4.12 (scenario B), the baseline operating cost factors are both set to 1.0. Projects that increase the operating costs are assigned factors >1.0 and those that decrease the costs are assigned to factors <1.0.

For a given scenario, the operating capital expenditure ratio, OP_{CE} is determined by:

$$OP_{CE} = OP_{CE,1} * OP_{CE,2} * OP_{CE,3} * ... * OP_{CE,n}$$

Here, $OP_{CE,1}$, $OP_{CE,2}$, $OP_{CE,3}$, and $OP_{CE,n}$, represent all the operating capital expenditure project factors for all projects selected in the scenario. Similarly, the operating effort ratio, OP_E is determined by:

$$OP_E = OP_{E,1} * OP_{E,2} * OP_{E,3} * ... * OP_{E,n}$$

Here, $OP_{E,1}$, $OP_{E,2}$, $OP_{E,3}$, and $OP_{E,n}$, represent all the operating effort project factors for all projects selected in the scenario. The operating capital expenditure project factors for the 21 project options range from 0.9 to 1.4. The *Reliability Upgrade Project*, with an operating capital expenditure factor of 0.9 is the only project to offer a reduction since implementation reduces the likelihood of unplanned malfunctions, and thus reduces the need for replacement/spare parts and repair service procurements. Larger scaling projects that add multiple machines/stations carry high capital expenditure factors from 1.2 - 1.4 due to the high maintenance costs associated with processing fluid consumption, replacement/spare parts, and service contracts. The operating effort factors for the individual projects range from 0.7 to 1.3. The

Auto OMF Project, with a factor of 0.7 offers the greatest reduction due to its implementation of machine learning to an onerous operator-based manual process. Scaling projects that add 2 or more staff were assigned the largest operating effort factors from 1.2 – 1.3. A full list of operating costs for each scenario considered can be found in tables A.1, A.2, A.3, and A.4.

4.8 Step 7: Assess and Compare Portfolio Options

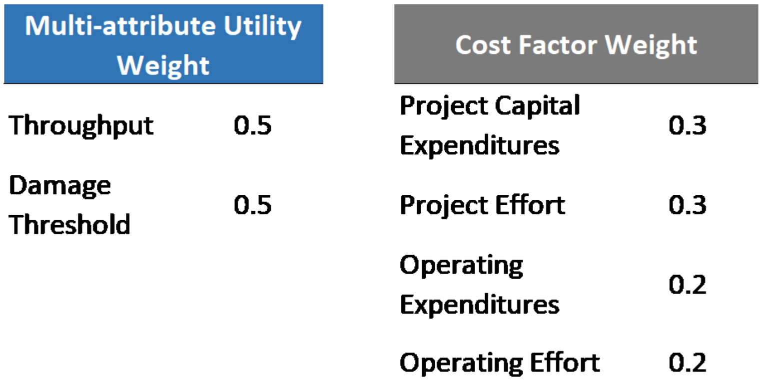
For the NIF ORL, the strategic drivers outlined in section 4.3.2 indicate that improvements in the key FOMs are desired to provide for the future needs of NIF. To assess each scenario, its value is derived using multi-attribute utility theory to aggregate its forecasted utility (based on throughput and optic damage threshold) and its estimated costs. Each scenario is then represented in single-attribute and multi-attribute tradespace plots to provide visual representations of the best scenario options based on the budgetary constraints.

4.8.1 Assigning Importance Weights and Aggregating Normalized Data

The NIF ORL overall strategy values optic throughput and optics damage threshold equally since both are needed for the system to retain value over time to its most important NIF stakeholders. From a cost perspective, project-related costs take slight precedence in importance when compared to operating costs. Table 4.13 shows the weights assigned.

These weight sets are used to strategically aggregate both the key system performance FOMs (throughput and damage threshold) and the key cost FOMs into 2 key indicators of each scenario's overall benefit and cost – the ***MAU*** (multi-attribute utility) and the ***Cost Factor***.

Prior to determining the ***MAU*** and the ***Cost Factor***, the FOM data sets for all scenarios are normalized to values between 0 and 1. The normalized value is



Multi-attribute Utility Weight	
Throughput	0.5
Damage Threshold	0.5

Cost Factor Weight	
Project Capital Expenditures	0.3
Project Effort	0.3
Operating Expenditures	0.2
Operating Effort	0.2

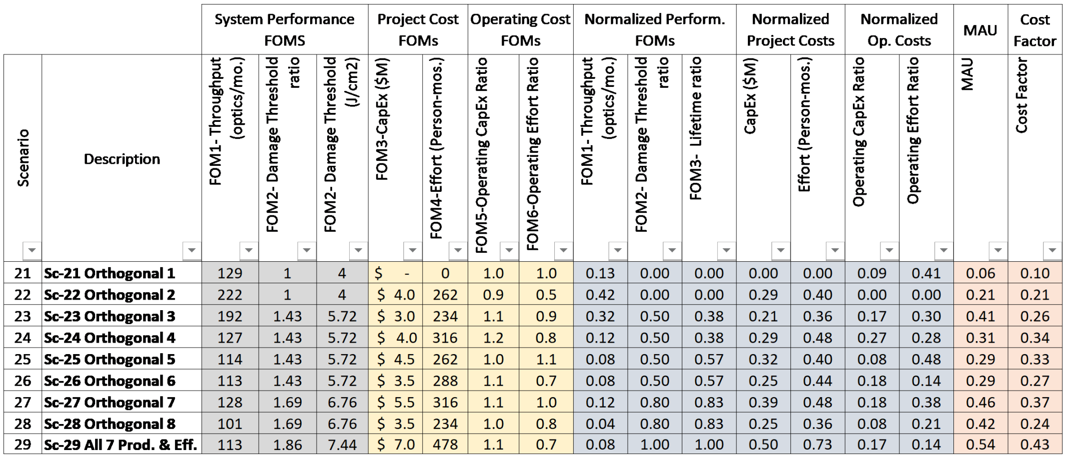
Table 4.13: A list of the multi-attribute utility and cost factor weights assumed

determined by the function:

$$z_i = \frac{x_i - min(x)}{max(x) - min(x)}$$

$$x = (x_i, ..., x_n)$$

Here, x represents a FOM or cost data set and z_i is the i^{th} normalized data. A partial list of the normalized data for scenarios 21 through 29 is shown in table 4.14. A complete list for all scenarios is available in tables A.1, A.2, A.3, and A.4.



		System Performance FOMS			Project Cost FOMs		Operating Cost FOMs		Normalized Perform. FOMs			Normalized Project Costs		Normalized Op. Costs		MAU	Cost Factor
Scenario	Description	FOM1- Throughput (optics/mo.)	FOM2- Damage Threshold ratio	FOM2- Damage Threshold (J/cm2)	FOM3-CapEx ($M)	FOM4-Effort (Person-mos.)	FOM5-Operating CapEx Ratio	FOM6-Operating Effort Ratio	FOM1- Throughput (optics/mo.)	FOM2- Damage Threshold ratio	FOM3- Lifetime ratio	CapEx ($M)	Effort (Person-mos.)	Operating CapEx Ratio	Operating Effort Ratio	MAU	Cost Factor
21	**Sc-21 Orthogonal 1**	129	1	4	$ -	0	1.0	1.0	0.13	0.00	0.00	0.00	0.00	0.09	0.41	0.06	0.10
22	**Sc-22 Orthogonal 2**	222	1	4	$ 4.0	262	0.9	0.5	0.42	0.00	0.00	0.29	0.40	0.00	0.00	0.21	0.21
23	**Sc-23 Orthogonal 3**	192	1.43	5.72	$ 3.0	234	1.1	0.9	0.32	0.50	0.38	0.21	0.36	0.17	0.30	0.41	0.26
24	**Sc-24 Orthogonal 4**	127	1.43	5.72	$ 4.0	316	1.2	0.8	0.12	0.50	0.38	0.29	0.48	0.27	0.28	0.31	0.34
25	**Sc-25 Orthogonal 5**	114	1.43	5.72	$ 4.5	262	1.0	1.1	0.08	0.50	0.57	0.32	0.40	0.08	0.48	0.29	0.33
26	**Sc-26 Orthogonal 6**	113	1.43	5.72	$ 3.5	288	1.1	0.7	0.08	0.50	0.57	0.25	0.44	0.18	0.14	0.29	0.27
27	**Sc-27 Orthogonal 7**	128	1.69	6.76	$ 5.5	316	1.1	1.0	0.12	0.80	0.83	0.39	0.48	0.18	0.38	0.46	0.37
28	**Sc-28 Orthogonal 8**	101	1.69	6.76	$ 3.5	234	1.0	0.8	0.04	0.80	0.83	0.25	0.36	0.08	0.21	0.42	0.24
29	**Sc-29 All 7 Prod. & Eff.**	113	1.86	7.44	$ 7.0	478	1.1	0.7	0.08	1.00	1.00	0.50	0.73	0.17	0.14	0.54	0.43

Table 4.14: A list containing the orthogonal array scenarios 21-28 and scenario 29 (All 7 Product and Efficiency Projects) showing normalized values, MAU, and Cost Factor

The ***MAU*** and the ***Cost Factor*** values are determined using the weighted linear additive preference function to aggregate the normalized data while considering the importance weights specified in table 4.13 [25]. For each scenario, the ***MAU*** and the ***Cost Factor*** are determined by multiplying the weight by its value for each of the 6 key FOMs and then summing the weighted values. The multi-attribute utility method applied to both the ***MAU*** and the ***Cost Factor*** for each scenario x is:

$$v(x) = \sum_{i=1}^{n} w_i * v_i(x_i)$$

where w_i is the importance weight, $v_i(x_i)$ is the value for a given scenario for its i^{th} attribute (the key FOMs), and n is the number of attributes [25].

4.8.2 Tradespace Exploration

With data estimating various benefits and costs established, we can further explore each scenario visually with single-attribute and multi-attribute plots. Single-attribute plots such as the *Throughput versus Project Capital Expenditures* plot shown in figure 4-20 can be useful in understanding the tradeoffs between two single attributes. Multi-attribute plots such as the *MAU versus Cost Factor* shown in figure 4-21 however contain the most useful information as aggregated key attribute values are displayed allowing for value-based selection of the most promising scenarios. Each plot contains 72 total data points representing all scenarios considered in this case study. The baseline scenario and scenarios 1 through 20 do not have DES-guided scaling sub-scenarios and are represented in the plot as single points. The DES-guided scaling sub-scenarios for scenarios 21 through 29 consist of 42 data points and are displayed in the plot with connections.

The trends in the *Throughput versus Project Capital Expenditures* plot (figure 4-20) indicate, as most would expect, that a trade-off exists between cost and throughout. The baseline scenario represents the presumed NIF ORL system prior to implementation of any of the projects considered and has a throughput of 129 optics/month and no project capital expenditures. As evident in the plot, a number of scenarios exist that decrease the throughput when only optics performance improvement projects

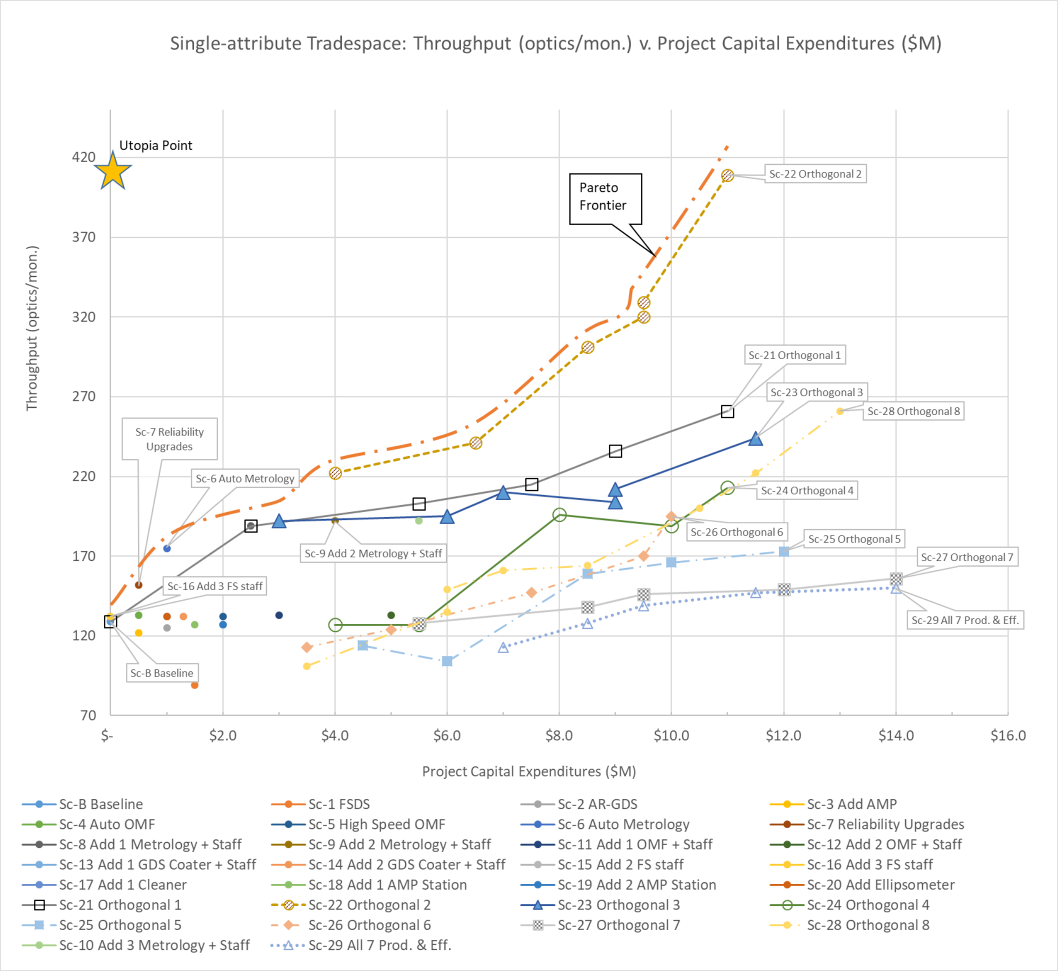
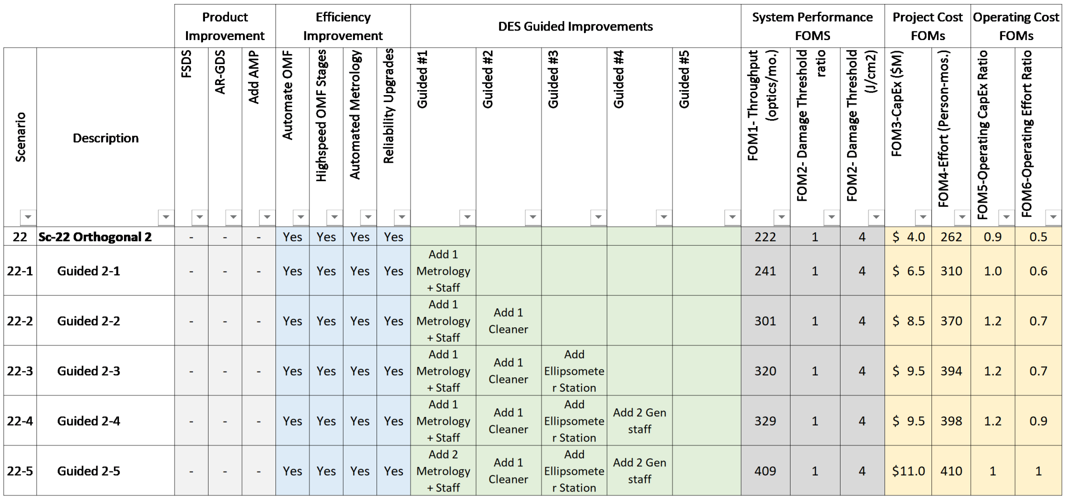


Figure 4-20: Single-attribute tradespace plot of *Throughput v. Project Capital Expenditures* displaying all scenarios and sub-scenarios modeled

are selected as part of the scenario. The monthly throughputs for all the scenarios considered range from as low as 89 optics/month due to the selection of a single optics performance improvement project (**Scenario 1 – FSDS**), to as high as 409 optics/month when only efficiency improvement projects are selected and bolstered by DES-guided scaling projects (sub-scenario 22-5). Project capital expenditures top out at $14M when numerous projects are selected as is the case with scenarios 27 and 29. Within the $4 - $11M range, scenario 22 (see table 4.15) and its 5 DES-guided sub-scenarios 22-1 to 22-5, dominate all other scenarios in throughput since they consider all four of the efficiency improvement projects (Automate OMF, High-speed OMF Stages, Automated Metrology, Reliability Upgrades) and none of the throughput-reducing optics performance improvement projects. If the NIF ORL system's stakeholders define benefit and cost simply as throughput and project capital expenditures, then these 5 scenarios would be outstanding, value-based options to consider for the project portfolio. Since however, the stakeholders value optics damage threshold in addition to throughput, this single-attribute tradespace plot can be explored to better understand optimal conditions to maximize throughput but should not be solely relied upon for value-based decision making.



		Product Improvement			Efficiency Improvement				DES Guided Improvements					System Performance FOMS			Project Cost FOMs		Operating Cost FOMs	
Scenario	Description	FSDS	AR-GDS	Add AMP	Automate OMF	Highspeed OMF Stages	Automated Metrology	Reliability Upgrades	Guided #1	Guided #2	Guided #3	Guided #4	Guided #5	FOM1- Throughput (optics/mo.)	FOM2- Damage Threshold ratio	FOM2- Damage Threshold (J/cm2)	FOM3-CapEx ($M)	FOM4-Effort (Person-mos.)	FOM5-Operating CapEx Ratio	FOM6-Operating Effort Ratio
22	**Sc-22 Orthogonal 2**	-	-	-	Yes	Yes	Yes	Yes						222	1	4	$ 4.0	262	0.9	0.5
22-1	**Guided 2-1**	-	-	-	Yes	Yes	Yes	Yes	Add 1 Metrology + Staff					241	1	4	$ 6.5	310	1.0	0.6
22-2	**Guided 2-2**	-	-	-	Yes	Yes	Yes	Yes	Add 1 Metrology + Staff	Add 1 Cleaner				301	1	4	$ 8.5	370	1.2	0.7
22-3	**Guided 2-3**	-	-	-	Yes	Yes	Yes	Yes	Add 1 Metrology + Staff	Add 1 Cleaner	Add Ellipsometer Station			320	1	4	$ 9.5	394	1.2	0.7
22-4	**Guided 2-4**	-	-	-	Yes	Yes	Yes	Yes	Add 1 Metrology + Staff	Add 1 Cleaner	Add Ellipsometer Station	Add 2 Gen staff		329	1	4	$ 9.5	398	1.2	0.9
22-5	**Guided 2-5**	-	-	-	Yes	Yes	Yes	Yes	Add 2 Metrology + Staff	Add 1 Cleaner	Add Ellipsometer Station	Add 2 Gen staff		409	1	4	$11.0	410	1	1

Table 4.15: List consisting of scenario 22 and its 5 sub-scenarios that maximize throughput by only considering throughput-increasing projects

The trends in the *Damage Threshold versus Project Capital Expenditures* plot (figure 4-22) also indicate that a trade-off exists between cost and damage threshold performance. The plot provides a clear visual representation of the limited resolution for damage threshold improvement as only 3 projects affect optic performance. Since the DES-guided sub-scenarios represent scaling projects that improve throughput but have no effect on optic performance, it makes sense that the sub-scenarios depicted in the plot all have the same damage threshold values as their parent scenarios. If the NIF ORL system's stakeholders define benefit and cost simply as damage threshold and project capital expenditures, then the 5 scenarios (scenarios 3, 2, 23, 28, and 29) representing the Pareto Frontier would be excellent portfolio options.

The multi-attribute plot *MAU versus Cost Factor* is similar to the *Throughput versus Project Capital Expenditures* and *Damage Threshold versus Project Capital Expenditures* plots but uses the normalized aggregated FOM values to plot the data points representing each scenario. When compared to the *Throughput versus Project Capital Expenditures* plot, scenario 22 and its sub-scenarios are no longer at the forefront of the Pareto frontier. Considerations made for damage threshold, and other cost considerations in this multi-attribute plot have pushed scenario 22 and its sub-scenarios down into a region dominated by 4-5 other scenarios and their sub-scenarios. Along the Pareto frontier, there are a number of intriguing scenarios all at varying cost factors. Within the lower cost factor range of .1 - .3, the five scenarios that dominate the region are scenarios 7, 6, 2, 28, and 23. In the higher cost factor range of .3 to .9, sub-scenarios 28-1 through 28-7 and scenario 29 and its sub-scenarios dominate the region. Each of these prospective scenarios represents the most or nearly the most utility (benefit) at a given cost and will be further explored.

4.8.3 Low-cost Region

The 5 scenarios listed in table 4.16 represent the best options within the low-cost factor region of .1 to .3. If project and operating budget projections are severely limited, scenario 7 only includes the *Reliability Upgrade Project* which is an economical way to improve throughput (129 to 152 optics/month) by upgrading problematic machines to greatly reduce the likelihood of unplanned malfunctions and faults to increase the machine's availability. The value proposition here is a 23 optics/month

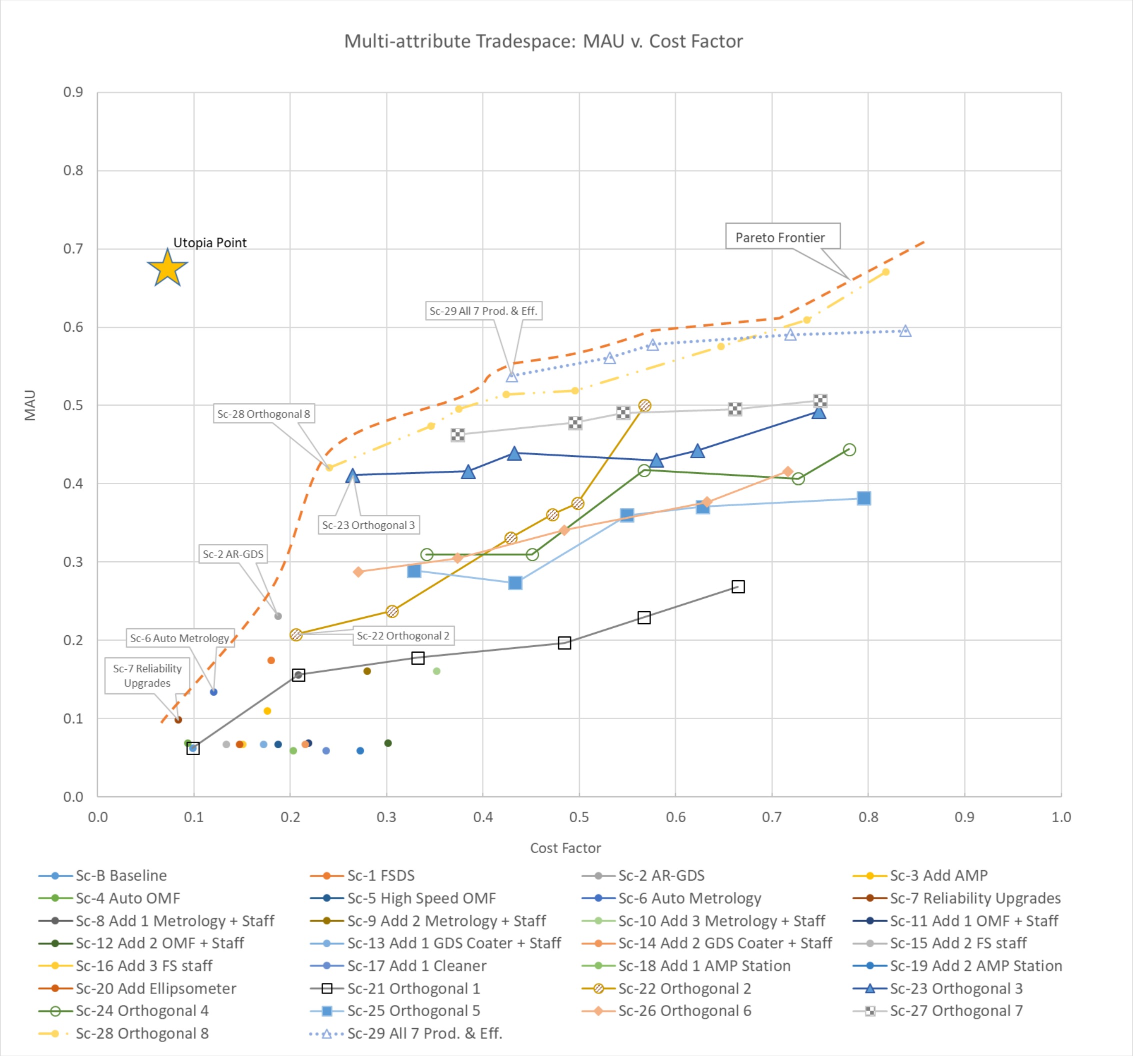


Figure 4-21: Multi-attribute tradespace plot of *MAU v. Cost Factor* displaying all scenarios and sub-scenarios modeled

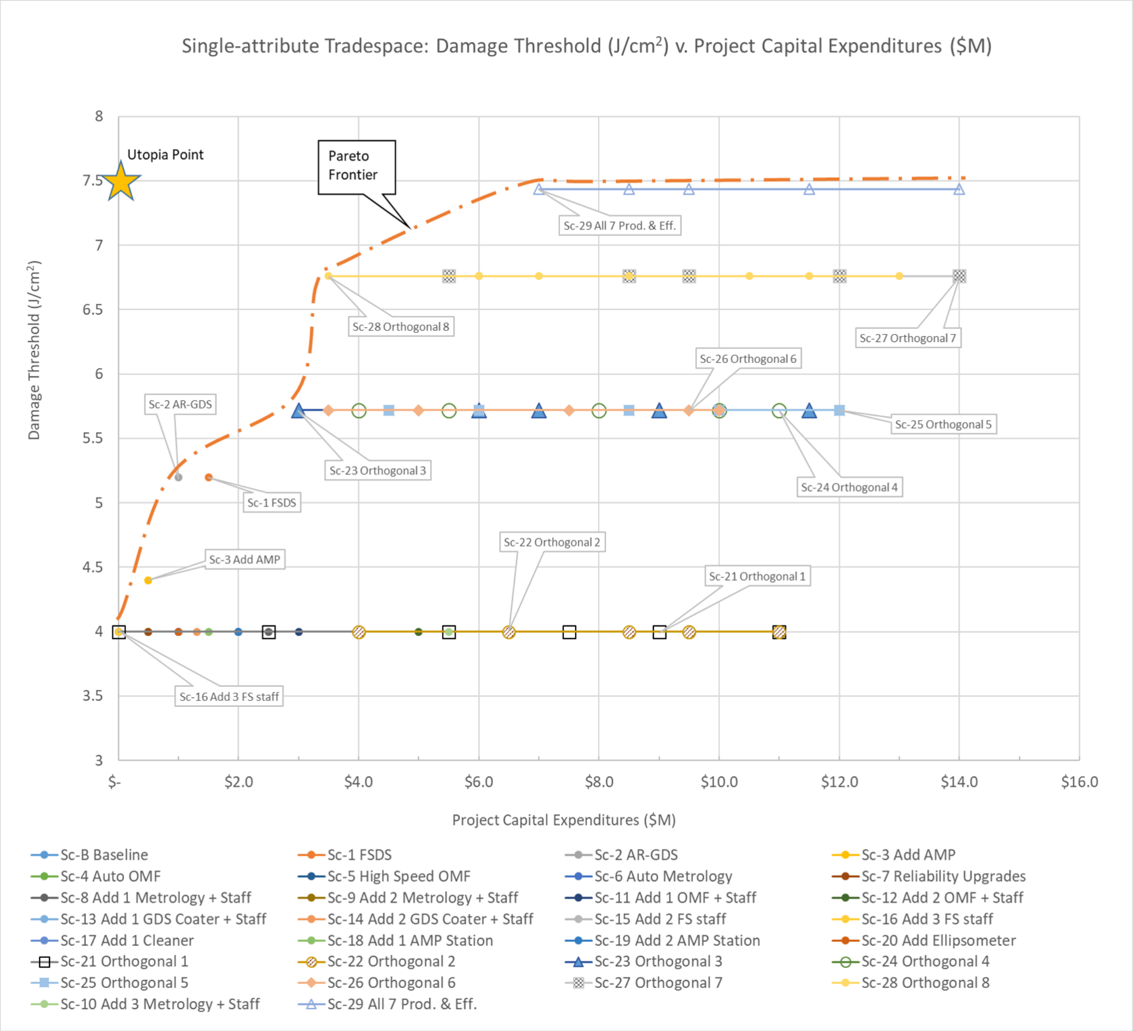


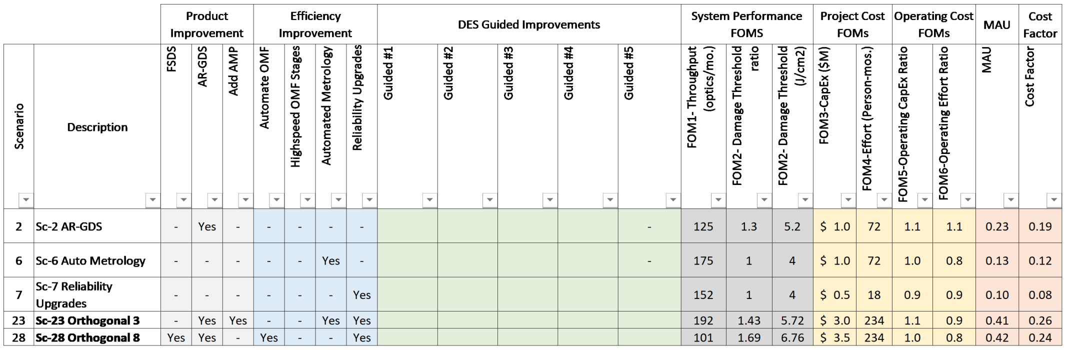
Figure 4-22: Single-attribute tradespace plot of *Damage Threshold v. Project Capital Expenditures* displaying all scenarios and sub-scenarios modeled

increase, a slight decrease in operating costs, at a cost of \$.5M in project capital expenditures and 18 person-months in effort. Similarly, scenario 6 only includes one efficiency improvement project (the *Auto Metrology Project*) forecasted to improve throughput with the introduction of machine learning technology. The value proposition is a 46 optics/month increase and a decrease in operating effort, at a cost of \$1M in project capital expenditures, and 72 person-months in effort. Scenario 2 also consists of just one project -the *AR-GDS Project* – and represents a slight increase in cost factor when compared to scenario 6 because coating an additional GDS optic surface is expected to require additional operating costs. The forecasted optic performance improvement and the relatively low throughput penalty make this an enticing low-cost option with an MAU of .25. The value proposition is a slight increase in optics damage threshold improvement at a cost of \$1.0M in project capital expenditures, 72 person-month effort, slightly increased operating costs, and a reduction in throughput by 4 optics/month.

The final 2 scenarios – scenarios 23 and 28 - in this cost range are located in a region where the Pareto frontier begins to bend towards the x-axis, therefore representing a decrease in MAU units gained per cost factor units spent. Because of this, these 2 scenarios are the preferred options in the low-cost region since the rate of gains in MAU units will be costlier moving forward. Both scenario 23 and scenario 28 incur additional costs as combined project scenarios consisting of 4 projects each but are still very economical as neither consist of costlier DES-guided scaling projects. Both scenarios consist of the *AR-GDS* and *Reliability Upgrades* projects and forecast to have similar project costs of \$3-3.5M and 234 person-months of effort. Selecting between these 2 scenarios is a matter of preference as scenario 23 forecasts for greater optic throughput (192 optics/month versus 101 optics/month) while scenario 28 is expected to provide a greater increase to the optics damage threshold.

4.8.4 Medium-cost Region

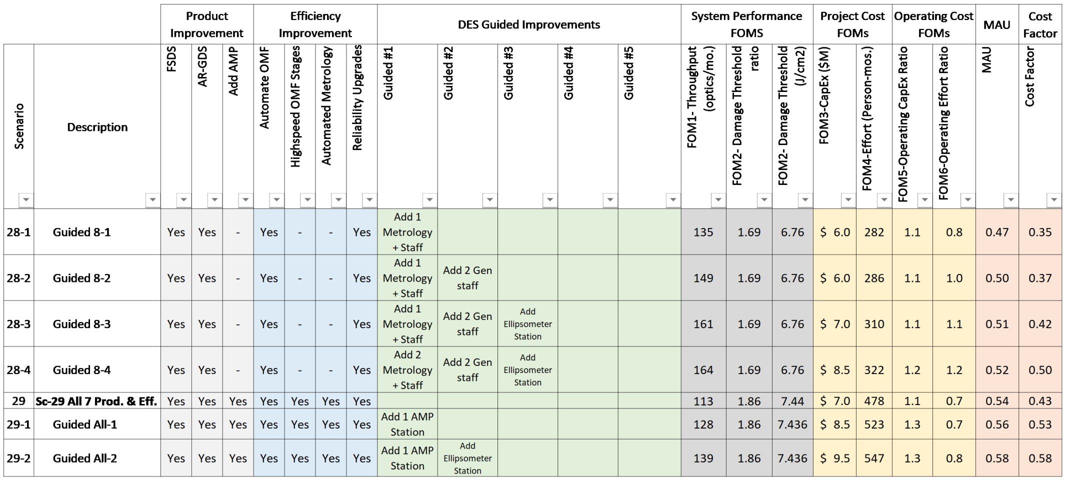
The 7 scenarios listed in table 4.17 represent the best options within the medium-cost region. In general, scenario 28's 4 projects selected – *FSDS*, *AR-GDS*, *Auto-*



		Product Improvement			Efficiency Improvement				DES Guided Improvements					System Performance FOMS			Project Cost FOMs		Operating Cost FOMs		MAU	Cost Factor
Scenario	Description	FSDS	AR-GDS	Add AMP	Automate OMF	Highspeed OMF Stages	Automated Metrology	Reliability Upgrades	Guided #1	Guided #2	Guided #3	Guided #4	Guided #5	FOM1- Throughput (optics/mo.)	FOM2- Damage Threshold ratio	FOM2- Damage Threshold (J/cm2)	FOM3-CapEx ($M)	FOM4-Effort (Person-mos.)	FOM5-Operating CapEx Ratio	FOM6-Operating Effort Ratio	MAU	Cost Factor
2	Sc-2 AR-GDS	-	Yes	-	-	-	-	-					-	125	1.3	5.2	$ 1.0	72	1.1	1.1	0.23	0.19
6	Sc-6 Auto Metrology	-	-	-	-	-	Yes	-					-	175	1	4	$ 1.0	72	1.0	0.8	0.13	0.12
7	Sc-7 Reliability Upgrades	-	-	-	-	-	-	Yes						152	1	4	$ 0.5	18	0.9	0.9	0.10	0.08
23	**Sc-23 Orthogonal 3**	-	Yes	Yes	-	-	Yes	Yes						192	1.43	5.72	$ 3.0	234	1.1	0.9	0.41	0.26
28	**Sc-28 Orthogonal 8**	Yes	Yes	-	Yes	-	-	Yes						101	1.69	6.76	$ 3.5	234	1.0	0.8	0.42	0.24

Table 4.16: The list of low-cost recommended scenarios based on their proximity to the Pareto frontier

mate OMF, and *Reliability Upgrades* – appear to be one of the more optimal project combinations. Scenario 28's sub-scenarios 28-1 through 28-4 offer DES-guided scaling projects added incrementally to provide higher throughput options for scenario 28. Scenario 29 considers all 7 of the optic performance and efficiency improvement projects. Scenario 29 and its sub-scenarios 29-1 dominate sub-scenarios 28-3 and 28-4, and are projected to offer better optics performance, but at a slightly lower throughput. While any of these scenarios in this region could be selected based on budgetary constraints and preferences, scenario 29 is recommended as this region's bending point where the rate of utility gain per cost begins to drop.

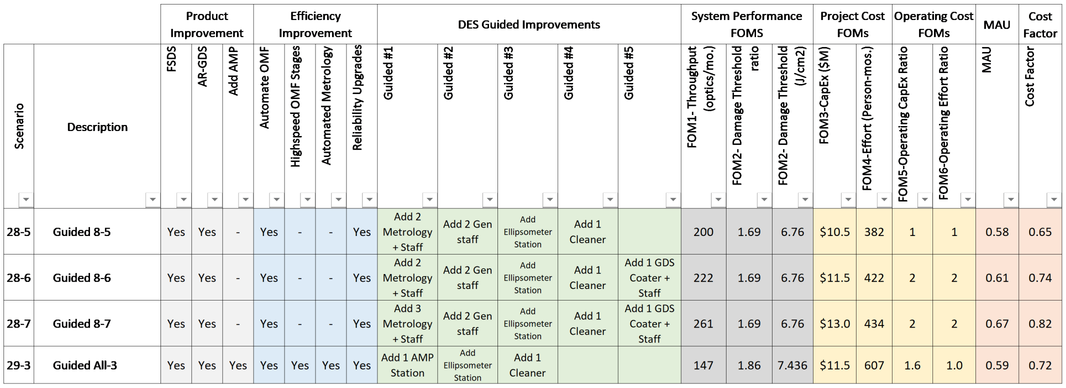


		Product Improvement			Efficiency Improvement				DES Guided Improvements					System Performance FOMS			Project Cost FOMs		Operating Cost FOMs		MAU	Cost Factor
Scenario	Description	FSDS	AR-GDS	Add AMP	Automate OMF	Highspeed OMF Stages	Automated Metrology	Reliability Upgrades	Guided #1	Guided #2	Guided #3	Guided #4	Guided #5	FOM1- Throughput (optics/mo.)	FOM2- Damage Threshold ratio	FOM2- Damage Threshold (J/cm2)	FOM3-CapEx ($M)	FOM4-Effort (Person-mos.)	FOM5-Operating CapEx Ratio	FOM6-Operating Effort Ratio	MAU	Cost Factor
28-1	Guided 8-1	Yes	Yes	-	Yes	-	-	Yes	Add 1 Metrology + Staff					135	1.69	6.76	$ 6.0	282	1.1	0.8	0.47	0.35
28-2	Guided 8-2	Yes	Yes	-	Yes	-	-	Yes	Add 1 Metrology + Staff	Add 2 Gen staff				149	1.69	6.76	$ 6.0	286	1.1	1.0	0.50	0.37
28-3	Guided 8-3	Yes	Yes	-	Yes	-	-	Yes	Add 1 Metrology + Staff	Add 2 Gen staff	Add Ellipsometer Station			161	1.69	6.76	$ 7.0	310	1.1	1.1	0.51	0.42
28-4	Guided 8-4	Yes	Yes	-	Yes	-	-	Yes	Add 2 Metrology + Staff	Add 2 Gen staff	Add Ellipsometer Station			164	1.69	6.76	$ 8.5	322	1.2	1.2	0.52	0.50
29	**Sc-29 All 7 Prod. & Eff.**	Yes	Yes	Yes	Yes	Yes	Yes	Yes						113	1.86	7.44	$ 7.0	478	1.1	0.7	0.54	0.43
29-1	Guided All-1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Add 1 AMP Station					128	1.86	7.436	$ 8.5	523	1.3	0.7	0.56	0.53
29-2	Guided All-2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Add 1 AMP Station	Add Ellipsometer Station				139	1.86	7.436	$ 9.5	547	1.3	0.8	0.58	0.58

Table 4.17: The list of medium-cost recommended scenarios based on their proximity to the Pareto frontier

4.8.5 High-cost Region

In the high-cost region of .65 cost factor and above, 4 dominant scenarios listed in table 4.18 represent the best options. These scenarios require \$10.5 to \$13M in project capital, 382 to 607 person-months in project effort, and involve a total of 8 to 10 projects. The MAU values are among the highest of all scenarios at .58 to .67 with gains in throughput and optics damage threshold. The sub-scenarios from scenario 28 continue to represent excellent value with DES-guided incremental scaling projects providing significant gains in throughput. Sub-scenario 29-3 is a good alternative to sub-scenario 28-6, offering greater optic performance improvements as opposed to higher throughput. The recommendation in this high-cost region is scenario 28-7. It is the costliest at a cost factor of .82 but offers a high rate of utility gain per cost when compared to the other scenarios in this region.

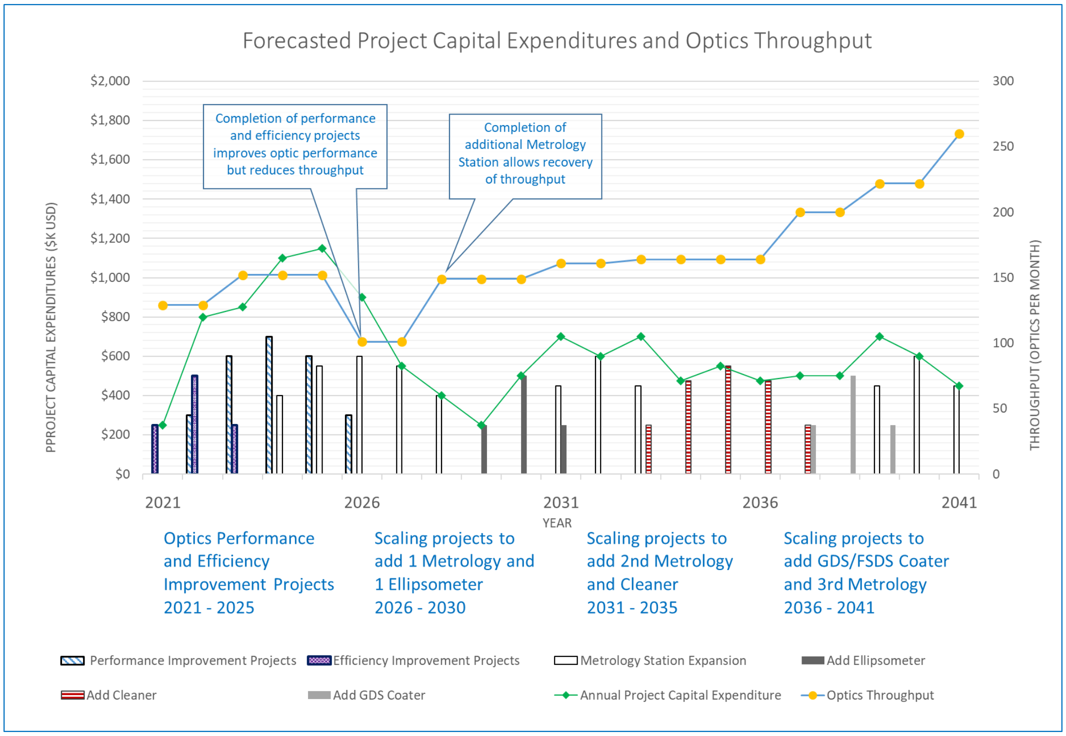


		Product Improvement			Efficiency Improvement				DES Guided Improvements					System Performance FOMS			Project Cost FOMs		Operating Cost FOMs		MAU	Cost Factor
Scenario	Description	FSDS	AR-GDS	Add AMP	Automate OMF	Highspeed OMF Stages	Automated Metrology	Reliability Upgrades	Guided #1	Guided #2	Guided #3	Guided #4	Guided #5	FOM1- Throughput (optics/mo.)	FOM2- Damage Threshold ratio	FOM2- Damage Threshold (J/cm2)	FOM3-CapEx (\$M)	FOM4-Effort (Person-mos.)	FOM5-Operating CapEx Ratio	FOM6-Operating Effort Ratio	MAU	Cost Factor
28-5	**Guided 8-5**	Yes	Yes	-	Yes	-	-	Yes	Add 2 Metrology + Staff	Add 2 Gen staff	Add Ellipsometer Station	Add 1 Cleaner		200	1.69	6.76	\$10.5	382	1	1	0.58	0.65
28-6	**Guided 8-6**	Yes	Yes	-	Yes	-	-	Yes	Add 2 Metrology + Staff	Add 2 Gen staff	Add Ellipsometer Station	Add 1 Cleaner	Add 1 GDS Coater + Staff	222	1.69	6.76	\$11.5	422	2	2	0.61	0.74
28-7	**Guided 8-7**	Yes	Yes	-	Yes	-	-	Yes	Add 3 Metrology + Staff	Add 2 Gen staff	Add Ellipsometer Station	Add 1 Cleaner	Add 1 GDS Coater + Staff	261	1.69	6.76	\$13.0	434	2	2	0.67	0.82
29-3	**Guided All-3**	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Add 1 AMP Station	Add Ellipsometer Station	Add 1 Cleaner			147	1.86	7.436	\$11.5	607	1.6	1.0	0.59	0.72

Table 4.18: The list of high-cost recommended scenarios based on their proximity to the Pareto frontier

4.9 Step 8: Select the Project Portfolio

Based on the strategic drivers to significantly raise the NIF ORL system's optic throughput and to improve optics performance, scenario 28-7 offers the best combination of projects to fund as the NIF ORL system's implementation project portfolio. It consists of 9 total projects with an estimated project cost of \$13M in capital expenditures and 434 person-months of effort. Project capital expenditures can be distributed over the 20-year roadmap period as shown in figure 4-23. Initial project capital costs grow to a peak of \$1.15M annually in 2025 to complete optics performance and efficiency improvement projects and eventually settle into the \$500k - \$700k range annually starting in 2030. One of the key strategies to maintain sufficient throughput is to sequence the completion of the efficiency improvement projects ahead of product improvement projects to help offset throughput reduction.



Forecasted Project Capital Expenditures and Optics Throughput

Completion of performance and efficiency projects improves optic performance but reduces throughput

Completion of additional Metrology Station allows recovery of throughput

Optics Performance and Efficiency Improvement Projects 2021 - 2025

Scaling projects to add 1 Metrology and 1 Ellipsometer 2026 - 2030

Scaling projects to add 2nd Metrology and Cleaner 2031 - 2035

Scaling projects to add GDS/FSDS Coater and 3rd Metrology 2036 - 2041

Figure 4-23: A plot of forecasted project capital expenditures and optics throughput showing a potential staggered project implementation plan for scenario 28-7. Individual project capital expenditures, annual project capital expenditures, and optics throughput are displayed over a 20-year period

By 2023, the *Automated OMF*, and *Reliability Upgrade* Projects will be completed to boost throughput from 129 to 152 optics/month to allow for a 3-year buildup of optics stock. By 2026, the *FSDS* and *AR-GDS* projects will be completed resulting in an increase in damage threshold from 4 to 6.7 J/cm^2 but a temporary 2-year long optics throughput reduction from 152 to 101 optics/month. Starting in 2024, scaling projects commence in a strategic sequence to optimally increase optic throughput. The DES-guided strategy is to expand metrology capacity first, followed by ellipsometry, cleaning, and then GDS coating. Metrology station capacity can be upgraded incrementally as shown in figure 4-23 to help distribute project costs.

By 2028, the scaling project to add a metrology station will be completed raising the optic throughput from 101 to 149 optics/month as shown in figure 4-24. By 2037, after the completion of another metrology station and a cleaning station, the optic throughput increases to 200 optics/month. By 2041, the last 2 projects within this project portfolio reach completion adding another metrology station and 1 GDS/FSDS coating station to increase throughput to 261 optics/month.

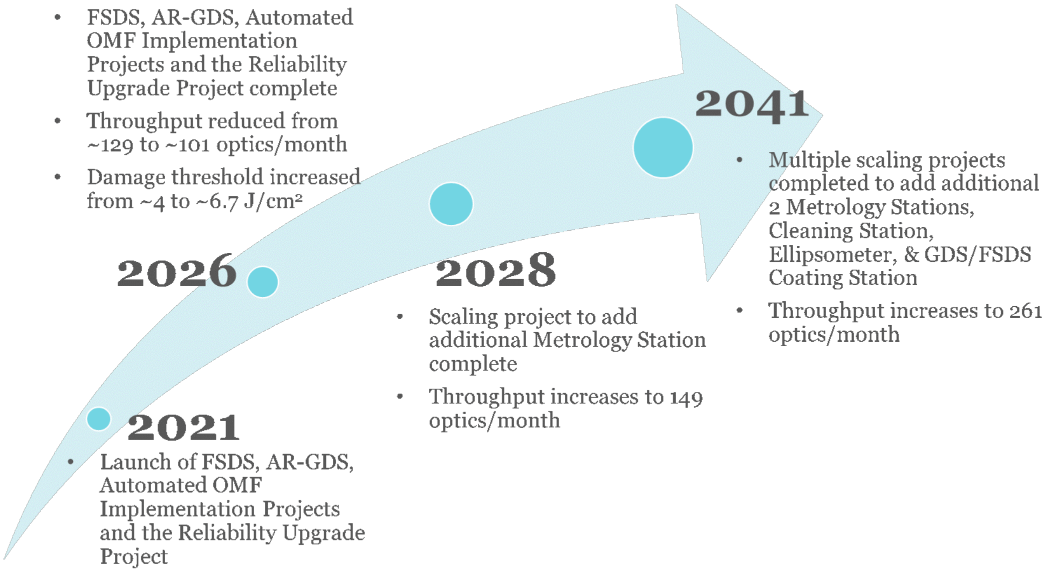


Figure 4-24: A schematic displaying the 20-year implementation plan for the proposed scenario 28-7 project portfolio

Chapter 5

Recommendations and Conclusions

The purpose of this research was to prescribe a practical framework that can be used by production system enterprises to strategically plan for phased system upgrades by considering multiple architectural options within a project portfolio design space evaluated by multiple objectives. This research is essential for production enterprises as a decision-making method for future investments. Technological advances continually offer investment opportunities to improve the production system's overall performance – including, but not limited to metrics such as throughput, product or service performance, and financial performance. With what economists call the Fourth Industrial Revolution - a period of significant technological advancement including, but not limited to automation, additive manufacturing, artificial intelligence, big data, machine learning, and IoT – upon us, investment decisions are expected to have profound effects on enterprise viability. With the use of a holistic, systematic method to align their investments to present and future industry needs, enterprise leaders can make well-informed decisions to optimize system performance (based on a given budget constraint), and maximize their competitive advantage within the industry.

New areas of Engineering Systems research – Enterprise System Architecting and Technology Roadmapping – offer holistic principles, methods, and tools to help guide organizations to meet their goals. They offer the foundation to build upon through adaption and selection of methods and techniques applicable to production systems.

The key questions the research sought to answer include:

- How can production system enterprises forecast future external landscapes and future stakeholder needs to strategically plan system architecture upgrades over time to maximize value?
- How do you identify key figures of merit (FOMs) to properly assess and track technology development?
- How do enterprises scout and assess technology and its usefulness to a production system?

The new framework proposed, based on Engineering Systems methods, is a credible method to both qualitatively, and quantitatively evaluate aspects of investment decisions. The use of this framework enables enterprise leaders to take a more holistic view to consider all systems – internal and external – that affect enterprise viability to generate and assess a set of investment options against criteria linked to key stakeholder value. Moreover, the framework proposed provides a strong basis for the recommendation of projects to pursue as a complete portfolio. The research yielded a number of relevant points that are summarized below:

- The holistic Engineering Systems approach to identifying stakeholder value is a key component found to be lacking in more traditional approaches to strategic production system planning
- Although quantitative models provide more accurate forecasts, the expertise required may lead to low adoption rates for enterprises with limited resources
- Some form of DES modeling is essential for production system modeling to forecast throughput and to identify process bottlenecks for the creation of incremental investment sub-scenarios
- The proposed framework is flexible, allowing the use of qualitative and quantitative methods of technical and financial modeling, but credibility is greatly

improved with the use of accurate, verified data (processing times, machine costs, operating costs, etc.) and validated quantitative models.

- As demonstrated in the case study, projects can simultaneously lead to the improvement of one key FOM (e.g., damage threshold) and the decline of another key FOM (e.g., throughput), creating a tradeoff scenario for assessment

While the framework proposed offers value to enterprise leaders as a tool for strategic production system planning, the insights offered can be improved with future work. One major future improvement would be integrating project risk as an essential decision-making criterion. The proposed framework recommends only considering projects that are based on mature, proven technology to limit the technical and schedule risk. Some projects can introduce significant risks to production systems as they may require shutting down an entire facility during the project construction or commissioning phases. Delays during these phases can lead to extended production downtime that can be detrimental to order fulfillment. Introducing a project risk ranking method would allow for risks to be considered. Furthermore, it would allow for the inclusion of projects based on less mature technology, leading to a larger design space, and thus a potentially larger solution space where acceptable risk levels can be considered.

Appendix A

Tables

		Product Improvement			Efficiency Improvement				DES Guided Improvements					System Performance FOMS			Project Cost FOMs		Operating Cost FOMs		Normalized Perform. FOMs			Normalized Project Costs		Normalized Op. Costs		MAU	Cost Factor
Scenario	Description	FSDS	AR-GDS	Add AMP	Automate OMF	Highspeed OMF Stages	Automated Metrology	Reliability Upgrades	Guided #1	Guided #2	Guided #3	Guided #4	Guided #5	FOM1- Throughput (optics/mo.)	FOM2- Damage Threshold ratio	FOM2- Damage Threshold (J/cm2)	FOM3-CapEx ($M)	FOM4-Effort (Person-mos.)	FOM5-Operating CapEx Ratio	FOM6-Operating Effort Ratio	FOM1- Throughput (optics/mo.)	FOM2- Damage Threshold ratio	FOM3- Lifetime ratio	CapEx ($M)	Effort (Person-mos.)	Operating CapEx Ratio	Operating Effort Ratio	MAU	Cost Factor
B	**Sc-B Baseline**	-	-	-	-	-	-	-					-	129	1	4	$ -	0	1.0	1.0	0.13	0.00	0.00	0.00	0.00	0.09	0.41	0.1	0.1
1	**Sc-1 FSDS**	Yes	-	-	-	-	-	-					-	89	1.3	5.2	$ 1.5	72	1.0	1.1	0.00	0.35	0.44	0.11	0.11	0.09	0.49	0.2	0.2
2	**Sc-2 AR-GDS**	-	Yes	-	-	-	-	-					-	125	1.3	5.2	$ 1.0	72	1.1	1.1	0.11	0.35	0.26	0.07	0.11	0.18	0.49	0.23	0.19
3	**Sc-3 Add AMP**	-	-	Yes	-	-	-	-					-	122	1.1	4.4	$ 0.5	72	1.1	1.1	0.10	0.12	0.09	0.04	0.11	0.18	0.49	0.11	0.18
4	**Sc-4 Auto OMF**	-	-	-	Yes	-	-	-					-	133	1	4	$ 0.5	72	1.0	0.7	0.14	0.00	0.00	0.04	0.11	0.09	0.16	0.07	0.09
5	**Sc-5 High Speed OMF**	-	-	-	-	Yes	-	-					-	132	1	4	$ 2.0	100	1.0	1.0	0.13	0.00	0.00	0.14	0.15	0.09	0.41	0.07	0.19
6	**Sc-6 Auto Metrology**	-	-	-	-	-	Yes	-					-	175	1	4	$ 1.0	72	1.0	0.8	0.27	0.00	0.00	0.07	0.11	0.09	0.24	0.13	0.12
7	**Sc-7 Reliability Upgrades**	-	-	-	-	-	-	Yes						152	1	4	$ 0.5	18	0.9	0.9	0.20	0.00	0.00	0.04	0.03	0.00	0.32	0.10	0.08
8	**Sc-8 Add 1 Metrology + Staff**	-	-	-	-	-	-	-	Add 1 Metrology + Staff	-				189	1	4	$ 2.5	48	1.1	1.1	0.31	0.00	0.00	0.18	0.07	0.18	0.49	0.2	0.2
9	**Sc-9 Add 2 Metrology + Staff**	-	-	-	-	-	-	-	Add 2 Metrology + Staff	-				192	1	4	$ 4.0	60	1.2	1.2	0.32	0.00	0.00	0.29	0.09	0.26	0.57	0.2	0.3
10	**Sc-10 Add 3 Metrology + Staff**	-	-	-	-	-	-	-	Add 3 Metrology + Staff					192	1	4	$ 5.5	72	1.3	1.3	0.32	0.00	0.00	0.39	0.11	0.35	0.65	0.2	0.4
11	**Sc-11 Add 1 OMF + Staff**	-	-	-	-	-	-	-	Add 1 OMF + Staff					133	1	4	$ 3.0	48	1.1	1.1	0.14	0.00	0.00	0.21	0.07	0.18	0.49	0.1	0.2
12	**Sc-12 Add 2 OMF + Staff**	-	-	-	-	-	-	-	Add 2 OMF + Staff					133	1	4	$ 5.0	60	1.2	1.2	0.14	0.00	0.00	0.36	0.09	0.26	0.57	0.1	0.3
13	**Sc-13 Add 1 GDS Coater + Staff**	-	-	-	-	-	-	-	Add 1 GDS Coater + Staff					132	1	4	$ 1.0	40	1.1	1.1	0.13	0.00	0.00	0.07	0.06	0.18	0.49	0.1	0.2
14	**Sc-14 Add 2 GDS Coater + Staff**	-	-	-	-	-	-	-	Add 2 GDS Coater + Staff					132	1	4	$ 1.3	45	1.2	1.2	0.13	0.00	0.00	0.09	0.07	0.26	0.57	0.1	0.2
15	**Sc-15 Add 2 FS staff**	-	-	-	-	-	-	-	Add 2 FS staff					132	1	4	$ -	4	1.0	1.2	0.13	0.00	0.00	0.00	0.01	0.09	0.57	0.1	0.1
16	**Sc-16 Add 3 FS staff**	-	-	-	-	-	-	-	Add 3 FS staff					132	1	4	$ -	6	1.0	1.3	0.13	0.00	0.00	0.00	0.01	0.09	0.65	0.1	0.2
17	**Sc-17 Add 1 Cleaner**	-	-	-	-	-	-	-	Add 1 Cleaner					127	1	4	$ 2.0	60	1.2	1.2	0.12	0.00	0.00	0.14	0.09	0.26	0.57	0.1	0.2
18	**Sc-18 Add 1 AMP Station**	-	-	-	-	-	-	-	Add 1 AMP Station					127	1	4	$ 1.5	45	1.2	1.1	0.12	0.00	0.00	0.11	0.07	0.26	0.49	0.1	0.2
19	**Sc-19 Add 2 AMP Station**	-	-	-	-	-	-	-	Add 2 AMP Station					127	1	4	$ 2.0	60	1.4	1.2	0.12	0.00	0.00	0.14	0.09	0.44	0.57	0.1	0.3
20	**Sc-20 Add Ellipsometer**	-	-	-	-	-	-	-	Add Ellipsometer Station					132	1	4	$ 1.0	24	1.0	1.1	0.13	0.00	0.00	0.07	0.04	0.09	0.49	0.1	0.1

Table A.1: List of full modeling results scenario B - scenario 20

		Product Improvement			Efficiency Improvement				DES Guided Improvements					System Performance FOMS			Project Cost FOMs		Operating Cost FOMs		Normalized Perform. FOMs			Normalized Project Costs		Normalized Op. Costs		MAU	Cost Factor
Scenario	Description	FSDS	AR-GDS	Add AMP	Automate OMF	Highspeed OMF Stages	Automated Metrology	Reliability Upgrades	Guided #1	Guided #2	Guided #3	Guided #4	Guided #5	FOM1- Throughput (optics/mo.)	FOM2- Damage Threshold ratio	FOM2- Damage Threshold (J/cm2)	FOM3-CapEx ($M)	FOM4-Effort (Person-mos.)	FOM5-Operating CapEx Ratio	FOM6-Operating Effort Ratio	FOM1- Throughput (optics/mo.)	FOM2- Damage Threshold ratio	FOM3- Lifetime ratio	CapEx ($M)	Effort (Person-mos.)	Operating CapEx Ratio	Operating Effort Ratio	MAU	Cost Factor
21	**Sc-21 Orthogonal 1**	-	-	-	-	-	-	-						129	1	4	$ -	0	1.0	1.0	0.13	0.00	0.00	0.00	0.00	0.09	0.41	0.06	0.10
21-1	Guided 1-1								Add 1 Metrology + Staff					189	1	4	$ 2.5	48	1.1	1.1	0.31	0.00	0.00	0.18	0.07	0.18	0.49	0.16	0.21
21-2	Guided 1-2	-	-	-	-	-	-	-	Add 1 Metrology + Staff	Add 1 OMF + Staff				203	1	4	$ 5.5	96	1.2	1.2	0.36	0.00	0.00	0.39	0.15	0.27	0.58	0.18	0.33
21-3	Guided 1-3	-	-	-	-	-	-	-	Add 1 Metrology + Staff	Add 1 OMF + Staff	Add 1 Cleaner			215	1	4	$ 7.5	156	1.5	1.5	0.39	0.00	0.00	0.54	0.24	0.49	0.77	0.20	0.48
21-4	Guided 1-4	-	-	-	-	-	-	-	Add 2 Metrology + Staff	Add 1 OMF + Staff	Add 1 Cleaner			236	1	4	$ 9.0	168	1.6	1.6	0.46	0.00	0.00	0.64	0.26	0.60	0.88	0.23	0.57
21-5	Guided 1-5	-	-	-	-	-	-	-	Add 2 Metrology + Staff	Add 2 OMF + Staff	Add 1 Cleaner			261	1	4	$ 11.0	180	1.7	1.7	0.54	0.00	0.00	0.79	0.27	0.73	1.00	0.27	0.66
22	**Sc-22 Orthogonal 2**	-	-	-	Yes	Yes	Yes	Yes						222	1	4	$ 4.0	262	0.9	0.5	0.42	0.00	0.00	0.29	0.40	0.00	0.00	0.21	0.21
22-1	Guided 2-1	-	-	-	Yes	Yes	Yes	Yes	Add 1 Metrology + Staff					241	1	4	$ 6.5	310	1.0	0.6	0.48	0.00	0.00	0.46	0.47	0.08	0.04	0.24	0.31
22-2	Guided 2-2	-	-	-	Yes	Yes	Yes	Yes	Add 1 Metrology + Staff	Add 1 Cleaner				301	1	4	$ 8.5	370	1.2	0.7	0.66	0.00	0.00	0.61	0.56	0.25	0.13	0.33	0.43
22-3	Guided 2-3	-	-	-	Yes	Yes	Yes	Yes	Add 1 Metrology + Staff	Add 1 Cleaner	Add Ellipsometer Station			320	1	4	$ 9.5	394	1.2	0.7	0.72	0.00	0.00	0.68	0.60	0.25	0.19	0.36	0.47
22-4	Guided 2-4	-	-	-	Yes	Yes	Yes	Yes	Add 1 Metrology + Staff	Add 1 Cleaner	Add Ellipsometer Station	Add 2 Gen staff		329	1	4	$ 9.5	398	1.2	0.9	0.75	0.00	0.00	0.68	0.61	0.25	0.31	0.38	0.50
22-5	Guided 2-5	-	-	-	Yes	Yes	Yes	Yes	Add 2 Metrology + Staff	Add 1 Cleaner	Add Ellipsometer Station	Add 2 Gen staff		409	1	4	$11.0	410	1	1	1.00	0.00	0.00	0.79	0.63	0.35	0.37	0.50	0.57
23	**Sc-23 Orthogonal 3**	-	Yes	Yes	-	-	Yes	Yes						192	1.43	5.72	$ 3.0	234	1.1	0.9	0.32	0.50	0.38	0.21	0.36	0.17	0.30	0.41	0.26
23-1	Guided 3-1	-	Yes	Yes	-	-	Yes	Yes	Add 1 OMF + Staff					195	1.43	5.72	$ 6.0	282	1.2	1.0	0.33	0.50	0.38	0.43	0.43	0.26	0.37	0.42	0.38
23-2	Guided 3-2	-	Yes	Yes	-	-	Yes	Yes	Add 1 OMF + Staff	Add Ellipsometer Station				210	1.43	5.72	$ 7.0	306	1.2	1.1	0.38	0.50	0.38	0.50	0.47	0.26	0.45	0.44	0.43
23-3	Guided 3-3	-	Yes	Yes	-	-	Yes	Yes	Add 1 OMF + Staff	Add Ellipsometer Station	Add 1 Cleaner			204	1.43	5.72	$ 9.0	366	1.4	1.3	0.36	0.50	0.38	0.64	0.56	0.47	0.62	0.43	0.58
23-4	Guided 3-4	-	Yes	Yes	-	-	Yes	Yes	Add 1 OMF + Staff	Add Ellipsometer Station	Add 1 Cleaner	Add 2 Gen staff		212	1.43	5.72	$ 9.0	370	1.4	1.5	0.38	0.50	0.38	0.64	0.56	0.47	0.83	0.44	0.62
23-5	Guided 3-5	-	Yes	Yes	-	-	Yes	Yes	Add 1 OMF + Staff	Add Ellipsometer Station	Add 1 Cleaner	Add 2 Gen staff	Add 1 Metrology + Staff	244	1.43	5.72	$11.5	418	2	2	0.48	0.50	0.38	0.82	0.64	0.60	0.95	0.49	0.75

Table A.2: List of full modeling results scenario 21 - scenario 23-5

		Product Improvement			Efficiency Improvement				DES Guided Improvements					System Performance FOMS			Project Cost FOMs		Operating Cost FOMs		Normalized Perform. FOMs			Normalized Project Costs		Normalized Op. Costs		MAU	Cost Factor
Scenario	Description	FSDS	AR-GDS	Add AMP	Automate OMF	Highspeed OMF Stages	Automated Metrology	Reliability Upgrades	Guided #1	Guided #2	Guided #3	Guided #4	Guided #5	FOM1- Throughput (optics/mo.)	FOM2- Damage Threshold ratio	FOM2- Damage Threshold (J/cm2)	FOM3-CapEx ($M)	FOM4-Effort (Person-mos.)	FOM5-Operating CapEx Ratio	FOM6-Operating Effort Ratio	FOM1- Throughput (optics/mo.)	FOM2- Damage Threshold ratio	FOM3- Lifetime ratio	CapEx ($M)	Effort (Person-mos.)	Operating CapEx Ratio	Operating Effort Ratio	MAU	Cost Factor
24	**Sc-24 Orthogonal 4**	-	Yes	Yes	Yes	Yes	-	-						127	1.43	5.72	$ 4.0	316	1.2	0.8	0.12	0.50	0.38	0.29	0.48	0.27	0.28	0.31	0.34
24-1	**Guided 4-1**	-	Yes	Yes	Yes	Yes	-	-	Add 1 AMP Station					127	1.43	5.72	$ 5.5	361	1.5	0.9	0.12	0.50	0.38	0.39	0.55	0.49	0.35	0.31	0.45
24-2	**Guided 4-2**	-	Yes	Yes	Yes	Yes	-	-	Add 1 AMP Station	Add 1 Metrology + Staff				196	1.43	5.72	$ 8.0	409	1.6	1.0	0.33	0.50	0.38	0.57	0.62	0.62	0.43	0.42	0.57
24-3	**Guided 4-3**	-	Yes	Yes	Yes	Yes	-	-	Add 1 AMP Station	Add 1 Metrology + Staff	Add 1 Cleaner			189	1.43	5.72	$10.0	469	1.9	1.2	0.31	0.50	0.38	0.71	0.72	0.90	0.59	0.41	0.73
24-4	**Guided 4-4**	-	Yes	Yes	Yes	Yes	-	-	Add 1 AMP Station	Add 1 Metrology + Staff	Add 1 Cleaner	Add Ellipsometer Station		213	1.43	5.72	$11.0	493	1.9	1.4	0.39	0.50	0.38	0.79	0.75	0.90	0.69	0.44	0.78
25	**Sc-25 Orthogonal 5**	Yes	-	Yes	-	Yes	-	Yes						114	1.43	5.72	$ 4.5	262	1.0	1.1	0.08	0.50	0.57	0.32	0.40	0.08	0.48	0.29	0.33
25-1	**Guided 5-1**	Yes	-	Yes	-	Yes	-	Yes	Add 1 AMP Station					104	1.43	5.72	$ 6.0	307	1.2	1.2	0.05	0.50	0.57	0.43	0.47	0.25	0.57	0.27	0.43
25-2	**Guided 5-2**	Yes	-	Yes	-	Yes	-	Yes	Add 1 AMP Station	Add 1 Metrology + Staff				159	1.43	5.72	$ 8.5	355	1.3	1.3	0.22	0.50	0.57	0.61	0.54	0.36	0.66	0.36	0.55
25-3	**Guided 5-3**	Yes	-	Yes	-	Yes	-	Yes	Add 1 AMP Station	Add 2 Metrology + Staff				166	1.43	5.72	$10.0	367	1.4	1.4	0.24	0.50	0.57	0.71	0.56	0.46	0.76	0.37	0.63
25-4	**Guided 5-4**	Yes	-	Yes	-	Yes	-	Yes	Add 1 AMP Station	Add 2 Metrology + Staff	Add 1 Cleaner			173	1.43	5.72	$12.0	427	1.7	1.7	0.26	0.50	0.57	0.86	0.65	0.72	1.00	0.38	0.80
26	**Sc-26 Orthogonal 6**	Yes	-	Yes	Yes	-	Yes	-						113	1.43	5.72	$ 3.5	288	1.1	0.7	0.08	0.50	0.57	0.25	0.44	0.18	0.14	0.29	0.27
26-1	**Guided 6-1**	Yes	-	Yes	Yes	-	Yes	-	Add 1 AMP Station					124	1.43	5.72	$ 5.0	333	1.3	0.7	0.11	0.50	0.57	0.36	0.51	0.37	0.20	0.30	0.37
26-2	**Guided 6-2**	Yes	-	Yes	Yes	-	Yes	-	Add 1 AMP Station	Add 1 Metrology + Staff				147	1.43	5.72	$ 7.5	381	1.5	0.8	0.18	0.50	0.57	0.54	0.58	0.49	0.26	0.34	0.48
26-3	**Guided 6-3**	Yes	-	Yes	Yes	-	Yes	-	Add 1 AMP Station	Add 1 Metrology + Staff	Add 1 Cleaner			170	1.43	5.72	$ 9.5	441	1.7	1.0	0.25	0.50	0.57	0.68	0.67	0.74	0.39	0.38	0.63
26-4	**Guided 6-4**	Yes	-	Yes	Yes	-	Yes	-	Add 2 AMP Station	Add 1 Metrology + Staff	Add 1 Cleaner			195	1.43	5.72	$10.0	456	2.0	1.1	0.33	0.50	0.57	0.71	0.70	1.00	0.47	0.42	0.72
27	**Sc-27 Orthogonal 7**	Yes	Yes	-	-	Yes	Yes	-						128	1.69	6.76	$ 5.5	316	1.1	1.0	0.12	0.80	0.83	0.39	0.48	0.18	0.38	0.46	0.37
27-1	**Guided 7-1**	Yes	Yes	-	-	Yes	Yes	-	Add 1 OMF + Staff					138	1.69	6.76	$ 8.5	364	1.2	1.1	0.15	0.80	0.83	0.61	0.56	0.27	0.46	0.48	0.50
27-2	**Guided 7-2**	Yes	Yes	-	-	Yes	Yes	-	Add 1 OMF + Staff	Add Ellipsometer Station				146	1.69	6.76	$ 9.5	388	1.2	1.2	0.18	0.80	0.83	0.68	0.59	0.27	0.55	0.49	0.55
27-3	**Guided 7-3**	Yes	Yes	-	-	Yes	Yes	-	Add 1 OMF + Staff	Add Ellipsometer Station	Add 1 Metrology + Staff			149	1.69	6.76	$12.0	436	1.3	1.3	0.19	0.80	0.83	0.86	0.67	0.38	0.64	0.50	0.66
27-4	**Guided 7-4**	Yes	Yes	-	-	Yes	Yes	-	Add 2 OMF + Staff	Add Ellipsometer Station	Add 1 Metrology + Staff			156	1.69	6.76	$14.0	448	1.5	1.4	0.21	0.80	0.83	1.00	0.68	0.49	0.74	0.51	0.75

Table A.3: List of full modeling results scenario 24 - scenario 27-4

		Product Improvement			Efficiency Improvement				DES Guided Improvements					System Performance FOMS			Project Cost FOMs		Operating Cost FOMs		Normalized Perform. FOMs			Normalized Project Costs		Normalized Op. Costs		MAU	Cost Factor
Scenario	Description	FSDS	AR-GDS	Add AMP	Automate OMF	Highspeed OMF Stages	Automated Metrology	Reliability Upgrades	Guided #1	Guided #2	Guided #3	Guided #4	Guided #5	FOM1- Throughput (optics/mo.)	FOM2- Damage Threshold ratio	FOM2- Damage Threshold (J/cm2)	FOM3-CapEx ($M)	FOM4-Effort (Person-mos.)	FOM5-Operating CapEx Ratio	FOM6-Operating Effort Ratio	FOM1- Throughput (optics/mo.)	FOM2- Damage Threshold ratio	FOM3- Lifetime ratio	CapEx ($M)	Effort (Person-mos.)	Operating CapEx Ratio	Operating Effort Ratio	MAU	Cost Factor
28	**Sc-28 Orthogonal 8**	Yes	Yes	-	Yes	-	-	Yes						101	1.69	6.76	$ 3.5	234	1.0	0.8	0.04	0.80	0.83	0.25	0.36	0.08	0.21	0.42	0.24
28-1	Guided 8-1	Yes	Yes	-	Yes	-	-	Yes	Add 1 Metrology + Staff					135	1.69	6.76	$ 6.0	282	1.1	0.8	0.14	0.80	0.83	0.43	0.43	0.17	0.27	0.47	0.35
28-2	Guided 8-2	Yes	Yes	-	Yes	-	-	Yes	Add 1 Metrology + Staff	Add 2 Gen staff				149	1.69	6.76	$ 6.0	286	1.1	1.0	0.19	0.80	0.83	0.43	0.44	0.17	0.41	0.50	0.37
28-3	Guided 8-3	Yes	Yes	-	Yes	-	-	Yes	Add 1 Metrology + Staff	Add 2 Gen staff	Add Ellipsometer Station			161	1.69	6.76	$ 7.0	310	1.1	1.1	0.23	0.80	0.83	0.50	0.47	0.17	0.49	0.51	0.42
28-4	Guided 8-4	Yes	Yes	-	Yes	-	-	Yes	Add 2 Metrology + Staff	Add 2 Gen staff	Add Ellipsometer Station			164	1.69	6.76	$ 8.5	322	1.2	1.2	0.23	0.80	0.83	0.61	0.49	0.25	0.57	0.52	0.50
28-5	Guided 8-5	Yes	Yes	-	Yes	-	-	Yes	Add 2 Metrology + Staff	Add 2 Gen staff	Add Ellipsometer Station	Add 1 Cleaner		200	1.69	6.76	$10.5	382	1	1	0.35	0.80	0.83	0.75	0.58	0.46	0.77	0.58	0.65
28-6	Guided 8-6	Yes	Yes	-	Yes	-	-	Yes	Add 2 Metrology + Staff	Add 2 Gen staff	Add Ellipsometer Station	Add 1 Cleaner	Add 1 GDS Coater + Staff	222	1.69	6.76	$11.5	422	2	2	0.42	0.80	0.83	0.82	0.64	0.59	0.89	0.61	0.74
28-7	Guided 8-7	Yes	Yes	-	Yes	-	-	Yes	Add 3 Metrology + Staff	Add 2 Gen staff	Add Ellipsometer Station	Add 1 Cleaner	Add 1 GDS Coater + Staff	261	1.69	6.76	$13.0	434	2	2	0.54	0.80	0.83	0.93	0.66	0.71	1.00	0.67	0.82
29	**Sc-29 All 7 Prod. & Eff.**	Yes	Yes	Yes	Yes	Yes	Yes	Yes						113	1.86	7.44	$ 7.0	478	1.1	0.7	0.08	1.00	1.00	0.50	0.73	0.17	0.14	0.54	0.43
29-1	Guided All-1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Add 1 AMP Station					128	1.86	7.436	$ 8.5	523	1.3	0.7	0.12	1.00	1.00	0.61	0.80	0.36	0.19	0.56	0.53
29-2	Guided All-2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Add 1 AMP Station	Add Ellipsometer Station				139	1.86	7.436	$ 9.5	547	1.3	0.8	0.16	1.00	1.00	0.68	0.84	0.36	0.25	0.58	0.58
29-3	Guided All-3	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Add 1 AMP Station	Add Ellipsometer Station	Add 1 Cleaner			147	1.86	7.436	$11.5	607	1.6	1.0	0.18	1.00	1.00	0.82	0.93	0.59	0.38	0.59	0.72
29-4	Guided All-4	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Add 1 AMP Station	Add Ellipsometer Station	Add 1 Cleaner	Add 1 Metrology + Staff		150	1.86	7.436	$14.0	655	1.7	1.1	0.19	1.00	1.00	1.00	1.00	0.73	0.46	0.60	0.84

Table A.4: List of full modeling results scenario 28 - scenario 29-4

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