Multidisciplinary System Design Optimization of Fiber-Optic Networks within Data Centers

By

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Abstract

The growth of the Internet and the vast amount of cloud-based data have created a need to develop data centers that can respond to market dynamics. The role of a data center designer, whom is responsible for scoping, building, and managing the infrastructure design is becoming increasingly complex. This work presents a new analytical systems approach to modeling fiber-optic network design within data centers. Multidisciplinary system design optimization (MSDO) is utilized to integrate seven disciplines into a unified software framework for modeling 10G, 40G, and 100G multi-mode fiber-optics networks: 1) market and industry analysis, 2) fiber-optic technology, 3) data center infrastructure, 4) systems analysis, 5) multi-objective optimization using genetic algorithms, 6) parallel computing, and 7) simulation research using MATLAB and OptiSystem. The framework is applied to four theoretical data center case studies to simultaneously evaluate the Pareto optimal trade-offs of (a) minimizing life-cycle costs, (b) maximizing user capacity, and (c) maximizing optical transmission quality (Q-factor). The results demonstrate that data center life-cycle costs are most sensitive to power costs, 10G OM4 multi-mode optical fiber is Pareto optimal for long reach and low user capacity needs, and 100G OM4 multi-mode optical fiber is Pareto optimal for short reach and high user capacity needs.

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To my wife and daughter, that have sacrificed time together to allow me to further develop myself, my deepest gratitude. I love you.

This work is dedicated to my children. I hope it serves as inspiration for you to design a meaningful future.

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Abbreviations and Acronyms

APD	Avalanche Photodiode
BER	Bit Error Rate
CPU	Central Processing Unit
dB	Decibel
EMBc	Calculated Effective Modal Bandwidth
EOR	End of Row
Gb	Gigabit
Gbps	Gigabit per Second
GB	Gigabyte
GBps	Gigabyte per Second
GFLOPS	Giga FLOPS (Floating Point Operations Per Second)
GPU	Graphic Processing Unit
HDA	Horizontal Distribution Application
HPC	High Performance Computing
IP	Internet Protocol
ISO	International Organization for Standardization
LAN	Local Area Network
LEED	Leadership in Energy and Environmental Design
MB/s	Megabyte per Second
Mbps	Megabit per Second
MDA	Main Distribution Area
MFD	Mode-Field Diameter
MMF	Multimode Fiber
MOGA	Multi-Objective Genetic Algorithm
MSDO	Multi-Disciplinary System Design Optimization
NA	Numerical Aperture
NAICS	North American Industry Classification System
OM1	Optical Multimode 1
OM2	Optical Multimode 2
OM3	Optical Multimode 3 – Laser Optimized
OM4	Optical Multimode 4 – Laser Optimized
OPD	Object-Process Diagram
OPL	Object-Process Language
OPM	Object-Process Methodology
OS1	Optical Singlemode 1
OS2	Optical Singlemode 2
OSNR	Optical Signal to Noise Ratio
OSNR	Optical Signal to Noise Ration
PIN	Intrinsic Photodiode
PUE	Power Usage Effectiveness
Q-factor	Ratio of signal power to noise power at the receiver to describe overall system quality.
RX	Receiver
SMF	Singlemode fiber
SPO	Single-Parameter Optimization
TIA-942A	Telecommunications Industry Association Standard for Data Centers 942-A
TIR	Total Internal Reflections
TOR	Top of Rack
TX	Transmitter
VCSEL	Vertical-Cavity Surface-Emitting Laser
WAN	Wide Area Network

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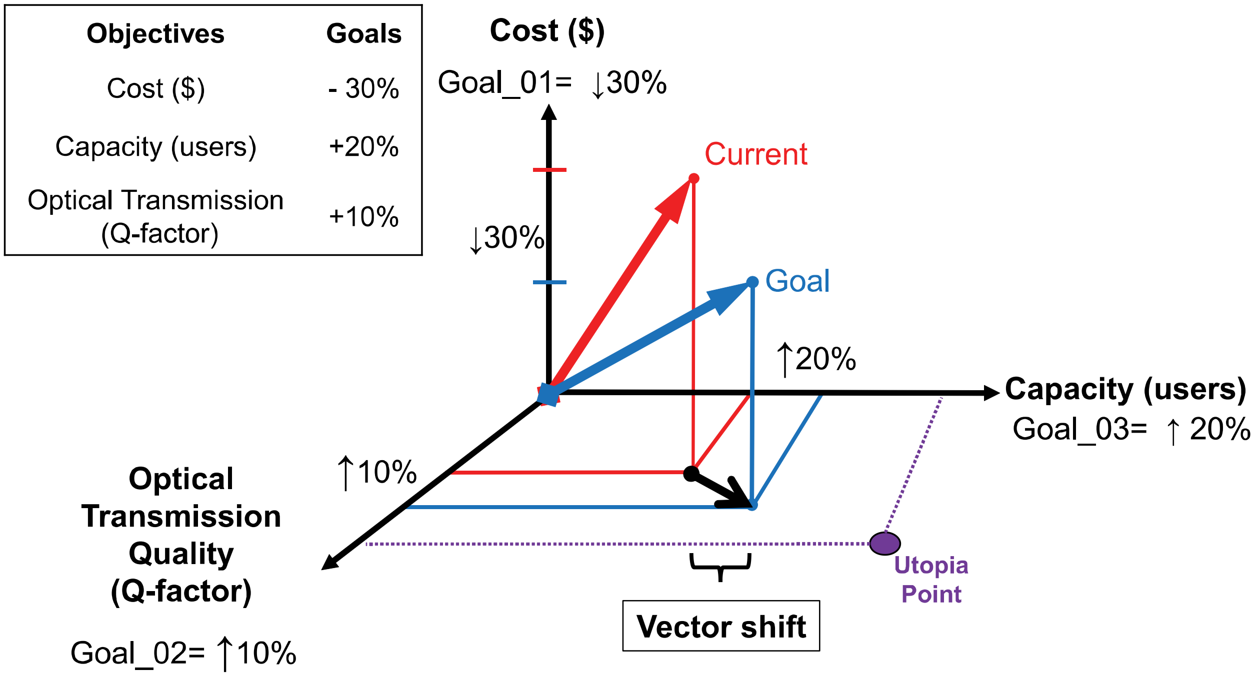
1 Introduction

At the time of writing this work, the US President has signed a new executive order, referred to as the National Strategic Computing Initiative (NSCI) [1], to build an exascale super-computer system [2]. The primary mandate of the NSCI initiative is to: “Establish hardware technology for future High-Performance System (HPC) systems.” It is the goal of this thesis to make a contribution in this field by considering a new multi-disciplinary and systems approach towards the design of the fiber-optic intra-connection network within data centers for the HPC systems to enable the optimized transport of data.

1.1 Motivation

The growth of the Internet and the vast amount of cloud-based data has created a need to build data centers that can respond to market, customer and technology dynamics, which includes: variability in demand, capacity planning, commoditization of hardware and services, globally accessible customers, political influences, and advances in new technology. The role of a decision maker, whom is responsible for scoping, building, and managing the data center infrastructure design is becoming increasingly complex. Yet, the practical resources for gaining insights into the possible design options are lacking; only those with exceptional computational and critical analytical skills are able to develop the foresight for the planning options. As shown by a 2005 Massachusetts Institute of Technology (MIT) data center planning study [3], the approaches to future data center design requires new ways of thinking about trade-offs and planning. In this work, I consider at a broad level, the data center design, and more specifically, the optical network within a data center.



Objectives	Goals
Cost ($)	- 30%
Capacity (users)	+20%
Optical Transmission (Q-factor)	+10%

Figure 1.1: Multi-Objective Goals for Fiber-Optic Network Planning

Shown in Figure 1.1 above is an example of a representation of three business dimensions that a business decision manager might consider when planning for a fiber-optic network. In the provided example, the x-axis is tracking the Capacity of the system in terms of simultaneous users; the y-axis is tracking the Costs ($); and the z-axis is tracking the Optical Transmission Quality in terms of Q-factor, a ratio of optical signal to noise estimation. The 'Current' vector represents the performance state of a current system and the 'Goal' vector represents the desired outcome of an implementation; in the provided example, the goal for Cost reduction is 30%, the Optical transmission quality is improved by 10%, and the Capacity increased by 20%. Performing this type of multi-objective goal mapping empowers the decision maker to understand the overall business direction and the potential changes required to the system life-cycle, which are not myopically focused on one aspect. The Utopia point represents the ideal (yet hypothetical) state, which in the example of Figure 1.1 above would represent zero optical loss, zero cost, and unlimited users—clearly not feasible, but worthwhile to consider in which direction and magnitude the decision maker should be optimizing the objectives.

1.2 Research Objectives

The main objective of this work is to develop a new and improved approach to modeling data center fiber-optic infrastructures system designs that can be used to address the following business operations concerns:

1. What are the key attributes needed to build a data center fiber-optic network?
2. What are the important factors for considering Pareto optimal data center fiber-optic networks?
3. How should data center vendor's best respond to new technology platforms?
4. How can data center providers address future commoditization of the infrastructure?
5. What skills will be important for the future-of-work to manage data center services?
6. What is the next phase of evolution for data center optical network design?

This work yields a practical decision support framework and computational process that can model the key parameters of a data center fiber-optic systems network design and facilitate a decision manager's ability to analytically consider the long-term life-cycle planning of resources.

1.3 Thesis statement

Utilizing a multidisciplinary systems design optimization (MSDO) [4] approach by integrating fiber-optic technology, systems-based analysis, multi-objective genetic algorithms, and parallel computation, provides enhanced insight towards considering trade-offs for minimizing life-cycle costs, maximizing capacity, and maximizing optical network performance of data center fiber-optic infrastructure design.

1.4 Research Methods

This work is divided into three phases: 1) Qualitative analysis consisting of interviews and background literature review, 2) Development of an integrated framework which builds up the framework and modeling approach, and 3) Case study analysis which explores four different ecosystems.

1.4.1 Phase 1: Qualitative analysis

A literature review of published information develops the underlying theory and approach for the thesis. Industry experts are interviewed to learn about the evolution of the data center and to understand more about the short-term and long-term concerns. The goal of this phase is to synthesize the background review and ascertain the design parameters to consider.

1.4.2 Phase 2: Integrated Decision Support Framework

Utilizing a holistic and integrative approach, the output of this phase is a new framework for engineers and management to use towards making practical decisions about data centers fiber-optic network design. The framework is developed using multi-objective genetic algorithms [5], and implemented in MATLAB [6] and OptiSystem [7]. The new software framework enables a decision-maker to run simulations and gain new insights about data center costs and optical network design.

1.4.3 Phase 3: Case Study Analysis

In this phase, four theoretical case studies, which increase in complexity, will be analyzed to determine which parameters are most important towards system life-cycle costs, user capacity, and optical performance. This work applies the integrated decision support framework as follows:

- **A)** Case Study 1: One cabinet within a data center (1 Cabinet).
- **B)** Case Study 2: One row of 10 cabinets within a data-center (10 Cabinets).
- **C)** Case Study 3: 10 rows of 10 cabinets within a data center (100 Cabinets).
- **D)** Case Study 4: Two sections of 10 rows of 10 cabinets within a data center (200 Cabinets).

The generalization behind utilizing the four configurations is to emulate potential groupings of cabinets, also known as Pods, and allow a data center manager to evaluate different potential designs.

1.5 Problem Statement

Table 1.1: Notation for Problem Statement

$\boldsymbol{OT_i} \triangleq$ Fiber-optic from Optical Transmitter
$\boldsymbol{TF_j} \triangleq$ Fiber-optic from Optical Transmitter
$\boldsymbol{OR_k} \triangleq$ Fiber-optic from Optical Transmitter
$\boldsymbol{M_l} \triangleq$ Optical Switch
$\boldsymbol{D_n} \triangleq$ Optical Switch
$\boldsymbol{R} \triangleq$ Data Rate Requirement
$\boldsymbol{TLC} \triangleq$ Total Lifecycle Cost
$\boldsymbol{UC} \triangleq$ User Capacity
$\boldsymbol{OTQ} \triangleq$ Optical Transmission Quality

The problem statement, represented visually in Figure 1.2 below, is defined as:

> How should OT_i, TF_j, OR_k, M_l, and D_n, be sized (a) and chosen (b), such that the data rate requirement R of the network is met, while minimizing total cost (TLC), maximizing user capacity (UC), and maximizing optical transmission quality (OTQ).

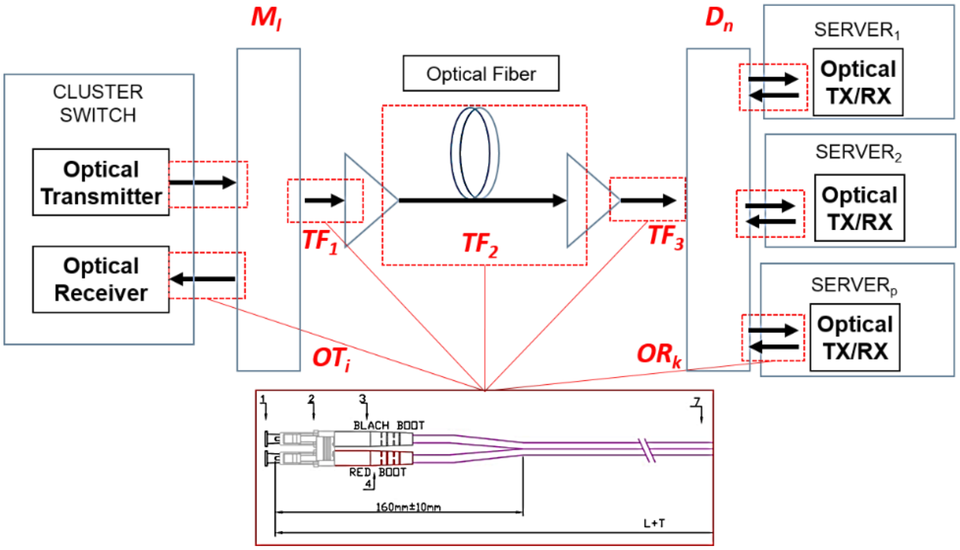


Figure 1.2: Representation of the Problem Statement
Adapted from [8], [9]

1.6 Summary of Research Contributions

This work provides a new approach to consider fiber-optic network systems design within data centers by:

1. Developing and presenting a new multidisciplinary system design optimization (MSDO) approach to considering multiple business objectives.
2. Defining a process to perform simulation using the new integrated MSDO approach.
3. Using the new approach to yield a Pareto front output to aid the decision manager towards developing an optimal strategy for system life-cycle planning.

Utilizing the approach developed in this work can help address the following business operational concerns:

1. What are the trade-offs between life-cycle cost, system capacity, and optical system quality?
2. What are the most sensitive parameters in the analysis?

1.7 Matrix of Related Work

Presented in Table 1.2 below is a matrix which systematically categorizes the literature that have influenced this thesis. The matrix is categorized horizontally by subject discipline and vertically by research topic. The numeric format of each citation, [##], is mapped to the Bibliography in Section 5.1.7.

Table 1.2: Summary Matrix of the Literature Review

Subject Discipline **Research Topics**	**Fiber-Optic Network Systems**	**Data Centers**	**Systems Analysis**	**Multi-Objective Optimization with Genetic Algorithms**	**Parallel Computing**	**Simulation Tools**
Introduction	[1][2][8][9]	[2][3]	[4][9]	[4][5]	[2]	[6][7][8]
Market Analysis	[10][11][12] [13][14][15] [16][17][18] [19][20][21] [22][23][24] [25][26][27] [28][29][30]	[3][31][32] [33][34][35]				
Topology	[36][37][38]	[39][40][41] [96][97]	[42][43][44][45] [46][47][48][49] [49][50][51][52] [53][54][55][56] [57][58][59][60] [61][62][63][64] [65][66][67][68] [69]			
Hierarchy		[47][48][70] [71][72]	[71][73][74][75] [76]			
OPM			[42][73][77]			
Design Optimization	[78][79][80] [81][82][83]	[3] [84]		[4][6][84][85] [86][87][88] [89][90]		
Genetic Algorithms				[4][5][6][87] [89][91][92] [93][94][95] [96][97][98]		
Sensitivity Analysis				[4][6]		
Pareto Frontier				[4][6]		
GPU Computing					[99][100][101] [102][103]	
Vectorized Functions					[86][91][92] [104][105] [106][107]	
CPU vs. GPU					[91][92][108] [109]	
OptiSystem	[7][110][111]					[110][111]
MATLAB	[6][8]				[85]	[8][103]
Conclusion	[112][113][114][115][116][117][118][119][120][121]					

1.8 Organization of the Work

Section 2 presents the literature review of the requisite background information and discussion about the prior research that have influenced the integrated framework developed in this work. ***Section 3*** presents the implementation of the work with a discussion of the problem statement, problem formulation, definition of the design vector, definition of the simulation model, representation of the ecosystem and tools for the analysis, and presents the numerical case study analysis with Pareto front analysis. Lastly, ***Section 4*** presents the conclusions and a discussion about the findings, insights, and recommendations to the future of data center optical network system.

2 Theory and Integrated Framework

The review of the literature synthesizes seven disciplines domains into an integrated framework:

1. Market and industry analysis;
2. Fiber optic technology;
3. Data Center Infrastructure;
4. Systems analysis;
5. Multi-objective optimization using genetic algorithms;
6. Parallel computing; and
7. Simulation research and tools using MATLAB and OptiSystem

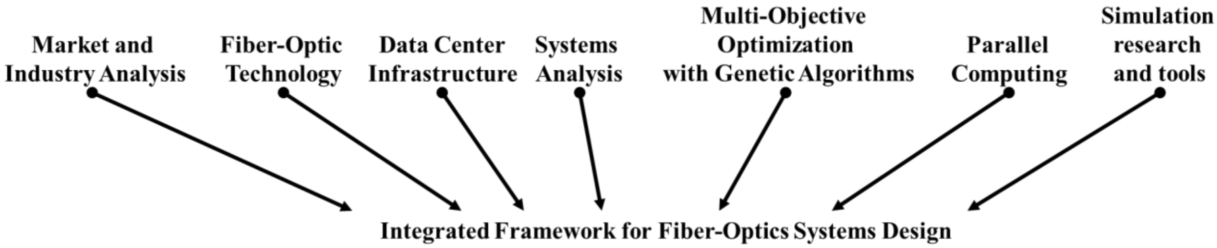


Figure 2.1: Summary of the Literature Review

The literature review and corresponding theories for each subject domain is presented independently in the subsequent sub-sections. The value this section provides is that it extracts the theories from the literature review and sets up the basis for the integrated software tool in Section 2.7.4 below.

2.1 Market Analysis

There are several important aspects to understand about the role of fiber-optics and the influence the US domestic market has on the growth of this technology. In the following Sections 2.1.1 - 2.1.7, is a discussion about the market drivers for fiber-optics telecommunications.

2.1.1 Data Center: Traffic Classes

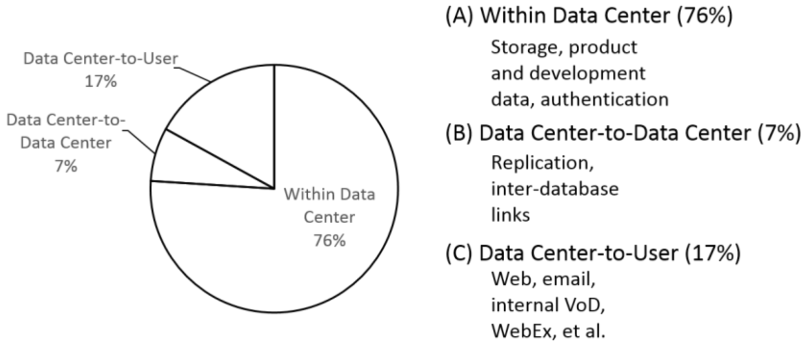


Figure 2.2: Broad Classes of Traffic Flow
Source: [33]

Driven by the large market demand for "Within Data Center" (76%) connectivity, as shown in Figure 2.2 above, the interest of this work to develop a better understanding of the challenges and make a contribution to a new approach to helping improve the overall efficiency of data center operations.

2.1.2 Regulation and Standards

There are several regulatory and standards organizations that currently drive the regulation of data centers. These standards are important to understand because they drive the infrastructure design considerations:

Hardware Safety:

Optical lasers standards for safety are defined by the International Electrotechnical Commission (IEC). The standards for the cables, which include fire safety for building codes and electrical interference are managed by the Underwriters Laboratories (UL) and Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment (RoHS).

SSAE16 Compliance:

These standards provide guidance to external auditors on Generally Accepted Auditing Standards (GAAS) in regards to auditing an entity and issuing a report." [10] [11]

ISO Certification:

"ISO (International Organization for Standardization) is an independent, non-governmental membership organization and the world's largest developer of voluntary International Standards. It is made up of over 162 member countries who are the national standards bodies around the world, with a Central Secretariat that is based in Geneva, Switzerland. ISO International Standards ensure that products and services are safe, reliable and of good quality. For business, they are strategic tools that reduce costs by minimizing waste and errors and increasing productivity. They help companies to access new markets, level the playing field for developing countries and facilitate free and fair global trade."[12]

LEED Certification:

"LEED certification is the most widely recognized, and widely used, green building program across the globe. LEED is a certification program for buildings, homes and communities that guides the design, construction, operations and maintenance. More than 54,000 projects are currently participating in LEED, comprising more than 10.1 billion square feet of space. There are four levels of certification - the number of points a project earns determines the level of LEED certification that the project will receive. Shown in Figure 2.3 below are the typical certification thresholds: Certified, Silver, Gold, and Platinum." [13]

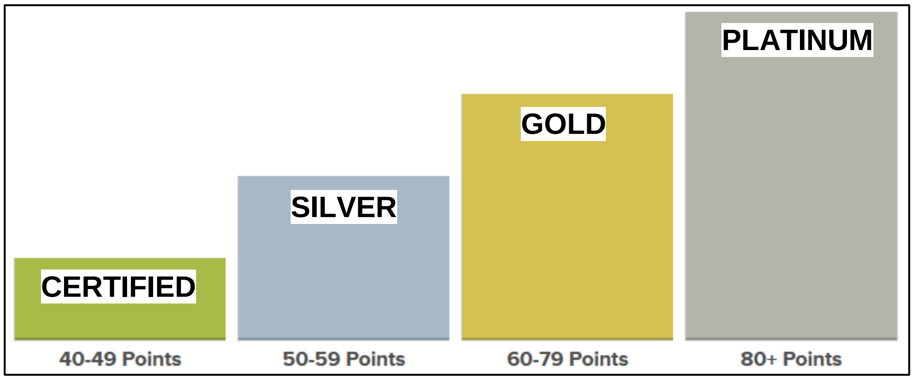


Figure 2.3: Four Levels of LEED Certification
Source: [13]

Uptime Institute:

“Uptime Institute is recognized globally for the creation and administration of the Tier Standards & Certifications for Data Center Design, Construction, and Operational Sustainability along with its Management & Operations reviews, FORCSS™ methodology, and energy efficiency initiatives.” [14]

Telecom Infrastructure Standard for Data Center:

“Standards projects and technical documents initiated by TIA's engineering committees are formulated according to the guidelines established by the TIA Engineering Committee Operating Procedures (ECOP) and the ANSI Essential Requirements. ANSI/TIA-942-A-1 was created by TIA Engineering Subcommittee TR-42.1 in response to switch manufacturers’ concerns about the structured cabling described in TIA-942-A. The traditional three-tier switch architecture needed additional content to fully enable the newer switch fabric architectures for data centers that support cloud computing to provide the low-latency, high bandwidth, any-to-any device network that cloud computing requires.” [15]

The ANSI-TIA standard:

“The Telecommunications Industry Association's TIA-942 Telecommunications Infrastructure Standard for Data Centers is an American National Standard that specifies the minimum requirements for telecommunications infrastructure of data centers and computer rooms including single tenant enterprise data centers and multi-tenant Internet hosting data centers. The topology proposed in the standard was intended to be applicable to any size data center. The standard was first published in 2005, following on the structured cabling work defined in TIA/EIA-568, and is often cited by companies such as ADC Telecommunications and Cisco Systems. The standard was updated with an addendum ANSI/TIA-942-A-1 in April 2013 from the TR-42.1 engineering subcommittee.” [34] The TIA-942 defines the type of infrastructure cabling, horizontal or backbone, in the different areas of a data center.

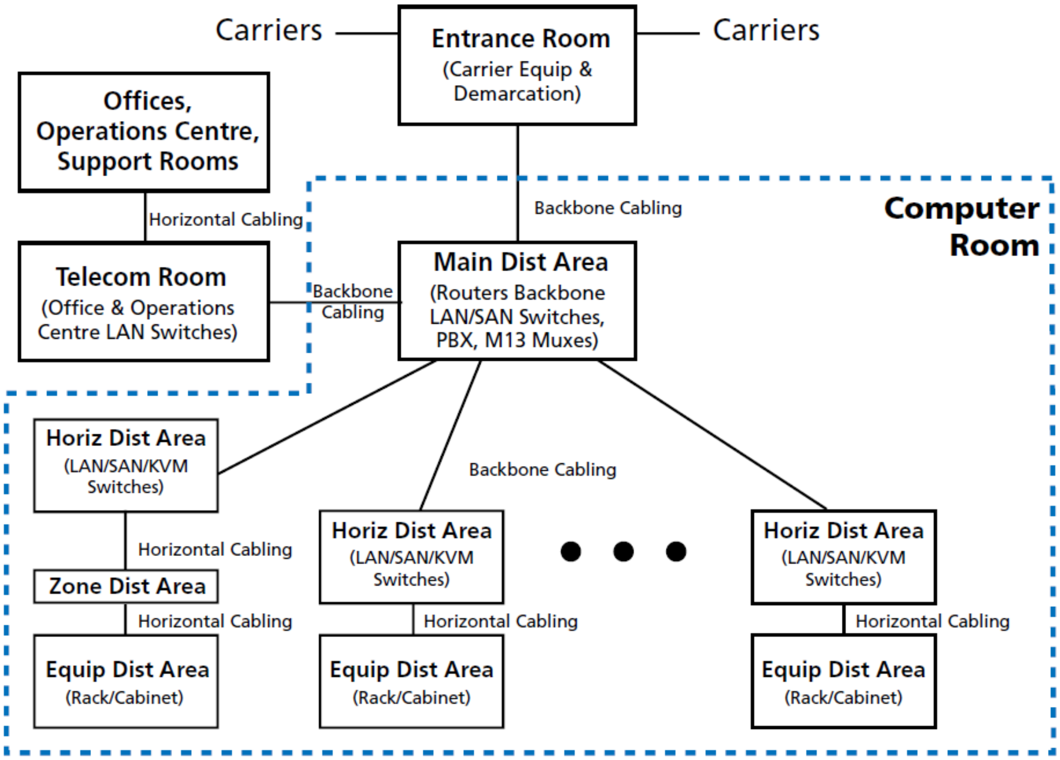


Figure 2.4: TIA-942 Telecommunications Data Center Infrastructure Standard Source: [40] [41]

National Telecommunications and Information Administration (**NTIA**):

"The NTIA is located within the Department of Commerce, is the Executive Branch agency that is principally responsible by law for advising the President on telecommunications and information policy issues. NTIA's programs and policymaking focus largely on expanding broadband Internet access and adoption in America, expanding the use of spectrum by all users, and ensuring that the Internet remains an engine for continued innovation and economic growth. These goals are critical to America's competitiveness in the 21st century global economy and to addressing many of the nation's most pressing needs, such as improving education, health care, and public safety." [16]

Specific NTIA activities include [16]:

- Administering grant programs that further the deployment and use of broadband and other technologies in America;
- Developing policy on issues related to the Internet economy, including online privacy, copyright protection, cybersecurity, and the global free flow of information online;
- Promoting the stability and security of the Internet's domain name system through its participation on behalf of the U.S. government in Internet Corporation for Assigned Names and Numbers (ICANN) activities; and
- Performing cutting-edge telecommunications research and engineering with both Federal government and private sector partners.
- NTIA is a leading source of research and data on the status of broadband adoption in America.

2.1.3 Growth

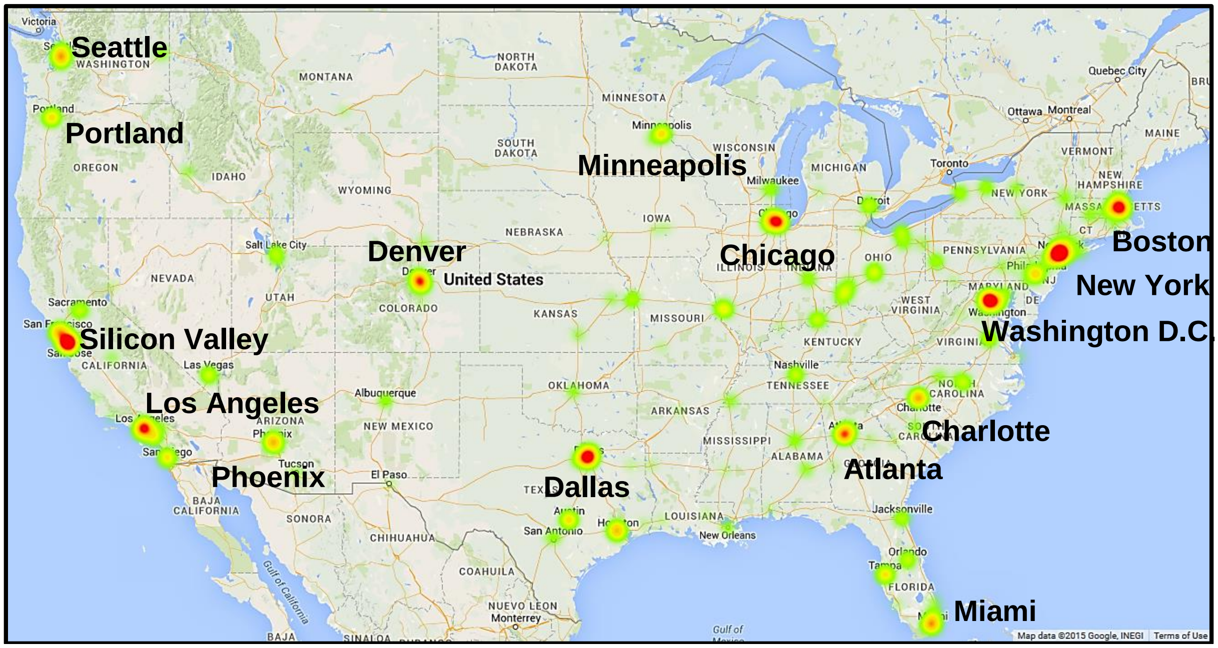


Figure 2.5: Density of Data Center Facilities (conus, n=1133)

Shown in Figure 2.5 above is a heat map representation of the geographic density of data center facilities in the continental USA. The source data was mined from publically available sources [35][17] and plotted using the Google Fusion tables developer service. The regions with the strongest density of facilities are indicated with the visual red-heat signature, include: Seattle, Portland, Silicon Valley, Los Angeles, Phoenix, Denver, Dallas, Minneapolis, Chicago, Atlanta, Miami, Washington D.C., New York, and Boston.

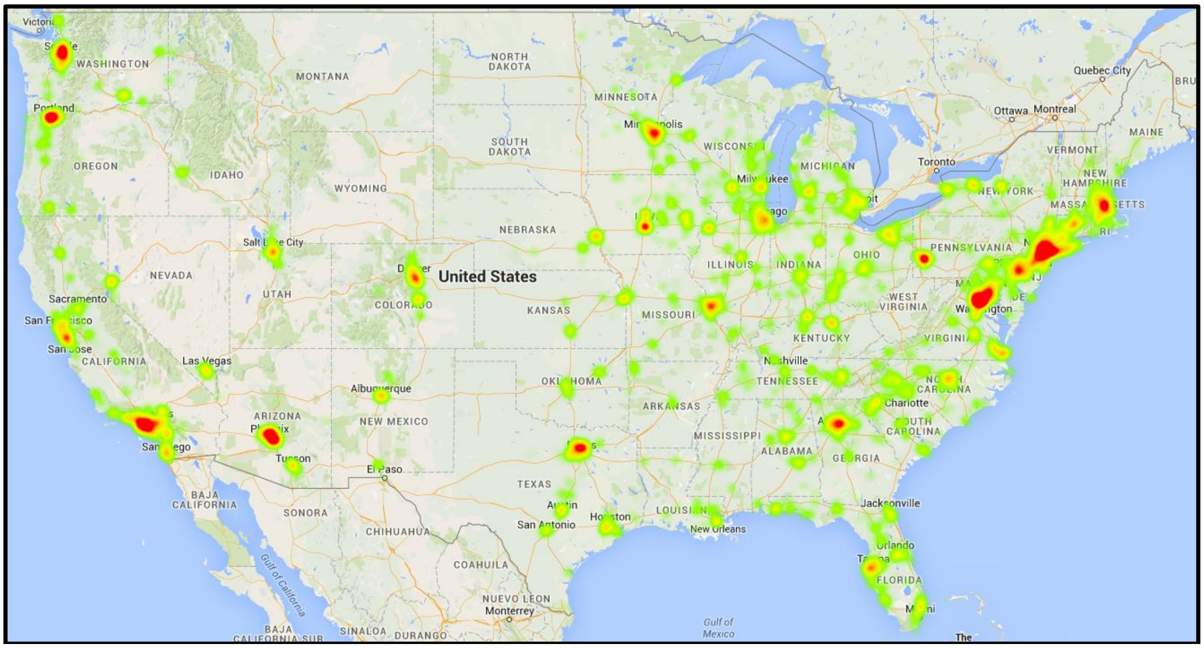


Figure 2.6: Density of Broadband, Weighted by Download Speed (conus, n=5758)

To understand the relationship that data centers have on Wide Area Network (WAN) interconnections, we can evaluate broadband speeds, as reported on the Federal Communications Commission “Measuring Fixed Broadband Report - 2014” download speed dataset (n=5758) [18], weighted by the influence of download speed, and mapped, as shown in Figure 2.6 above, using the Google Fusion tables. Presented in Table 2.1 below we observe that the fastest interconnection speeds (red heat signature of Figure 2.6) closely parallel the dominant locations of the data centers of Figure 2.5.

Table 2.1: Cities with Highest Data Center Density and Cities with Fastest Internet Speeds

Highest Data Center Density [Figure 2.5]	Fastest Internet Speeds [Figure 2.6]
Seattle	Seattle
Portland	
Silicon Valley	Silicon Valley
Los Angeles	Los Angeles
Phoenix	Phoenix
Denver	Denver
Dallas	Dallas
Minneapolis	Minneapolis
Chicago	Chicago
Atlanta	Atlanta
Miami	
Washington D.C.,	Washington D.C.,
New York	New York
Boston	Boston

From the comparative analysis of Table 2.1 above, we come to understand that a data center not only plays an important role for the distributed storage and continuous operations of computer servers, but also provides a connection point nexus for a Wide Area Network. To illustrate the role of the data center as an interconnection point, presented in Figure 2.7 below is the fiber-optic network for Level3 Communications, Inc., a dominant leader in network services.

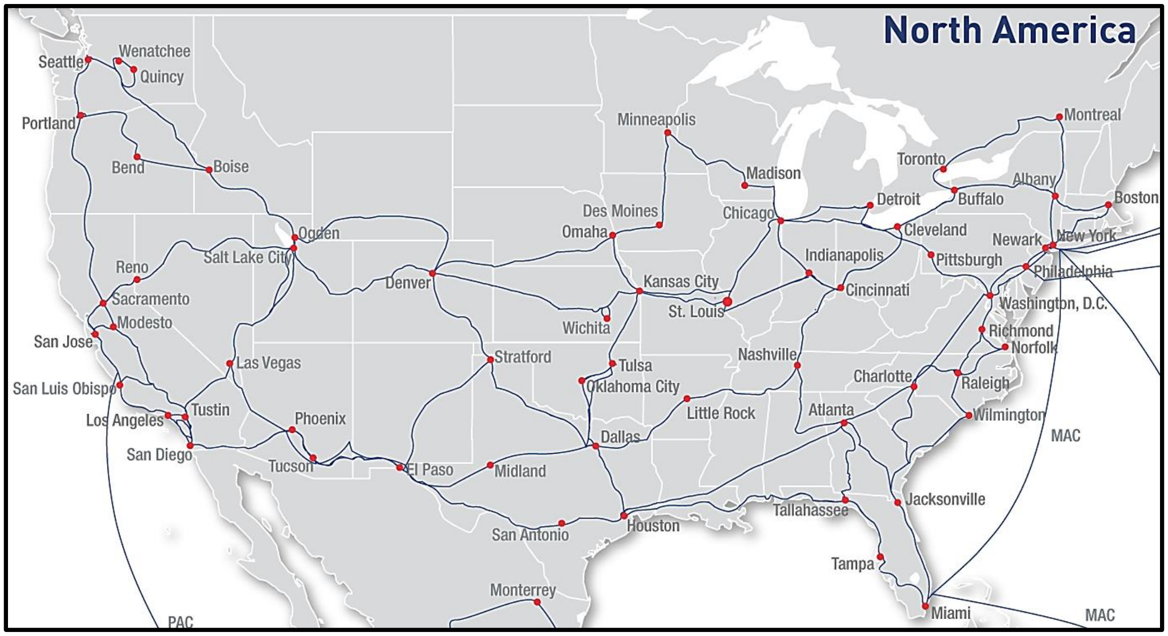


Figure 2.7: Level3 Communications Inc. Fiber Optic Network
Source: [19]

The fiber-optic routes are all interconnected at data center facilities that are common to Figure 2.5 and Figure 2.6. Therefore, we come to realize that the data center has become a critical component of infrastructure for sustaining our modern nationwide telecommunications infrastructure and the importance of proper planning within the data center plays a significant role in overall cost management.

To expand our understanding further about the role that data centers have on our society, we can evaluate the impact that data centers have on our economy by analysis of the U.S. Census Bureau Labor and Statistic NAICS Code 518210 [20], a widely used standard that the US Federal government uses for procurement of data center services, defined as:

> **518210 Data Processing, Hosting, and Related Services - 2007 NAICS Code**
> “This industry comprises establishments primarily engaged in providing infrastructure for hosting or data processing services. These establishments may provide specialized hosting activities, such as web hosting, streaming services or application hosting, provide application service provisioning, or may provide general time-share mainframe facilities to clients. Data processing establishments provide complete processing and specialized reports from data supplied by clients or provide automated data processing and data entry services.”

Presented in Figure 2.8 below is the NAICS 518210 U.S. Census Zip Code Business Pattern data for the number of establishments, employing at least 19 individuals for years 2004 to 2013 [21]. From this analysis, we observe that the trend for the data center industry is economic growth.

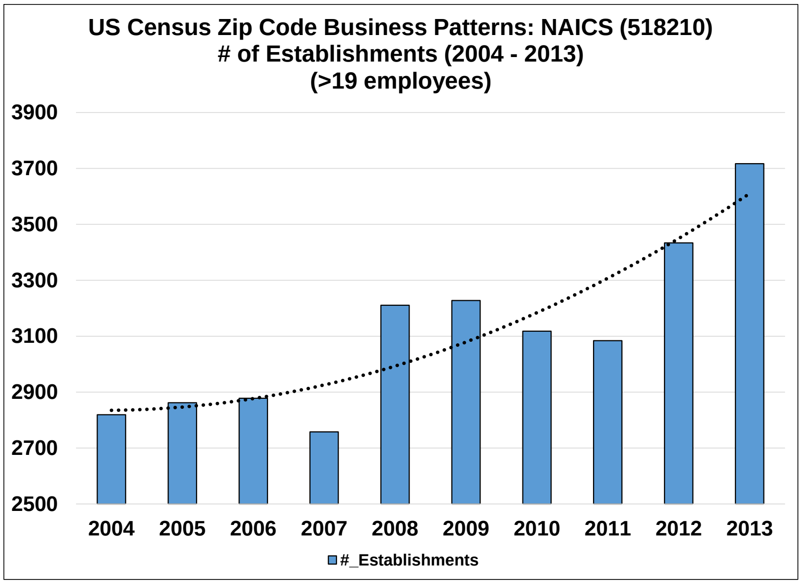


Figure 2.8: US County & Zip Code Business Patterns: NAICS 518210

Lastly, to understand the growth, we look to the Gartner Magic Quadrant Cloud Infrastructure as a Service [26], Figure 2.9 below, to learn about the current players in the market with clear identification of world-class companies like Amazon, Microsoft, Google, and VMWare on the leading edge.

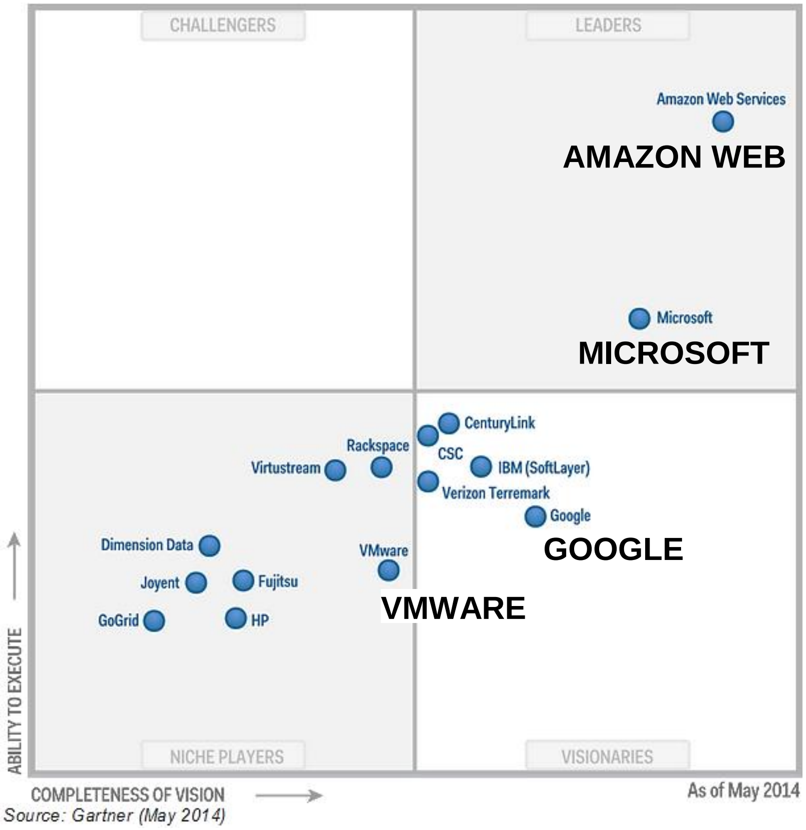


Figure 2.9: Magic Quadrant for Cloud Infrastructure as a Service
Source: [26]

To understand in which direction to develop the research, we turn to the Gartner Hype Cycle for Communication Service Provider Infrastructure [27], Figure 2.10 below, to understand how a technology is expected to perform, with a past-present-future perspective.

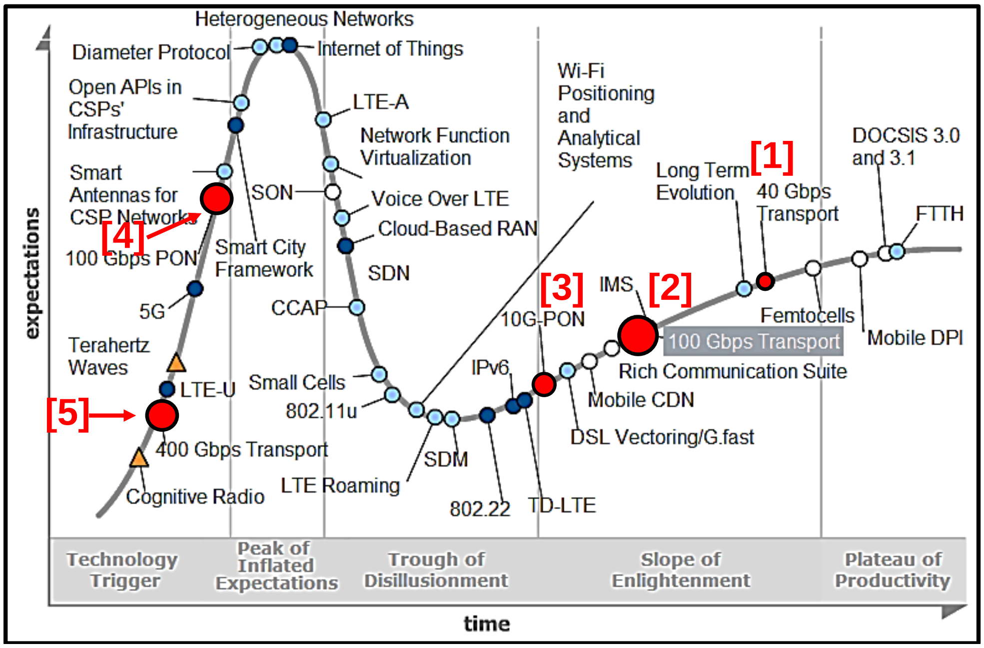


Figure 2.10: Hype Cycle for Communications Service Provider Infrastructure, 2014
Source: [27]

Shown in Figure 2.10 above is a Gartner Hype Cycle plot with technological expectation on the y-axis and time along the x-axis, which is divided into five epochs: Technology Triggers, Peak of Inflated Expectations, Trough of Disillusionment, Slope of Enlightenment, and Plateau of Productivity. We observe in [1], [2], [3], and [4] that 10G, 40G, and 100G speeds are technologies of the current era and that 400G [5] has now entered the timeline. These fiber-optic based technologies represent the current and future fiber-optic technologies that will be driving the critical infrastructure for data center telecommunications. This Gartner study helps us further understand the trends for optical communications are shifting towards 100G and beyond.

2.1.4 Technology Adoption Life-Cycle (TALC)

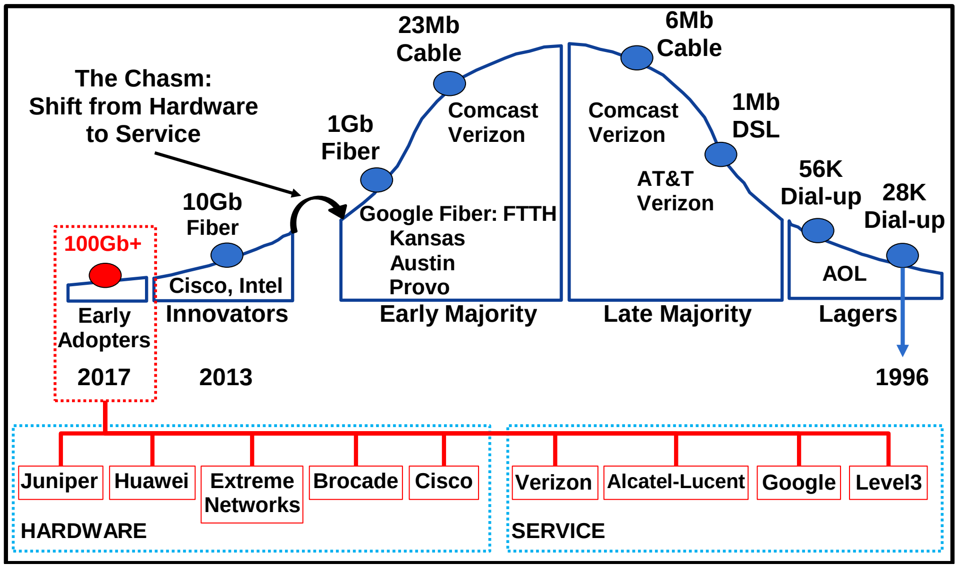
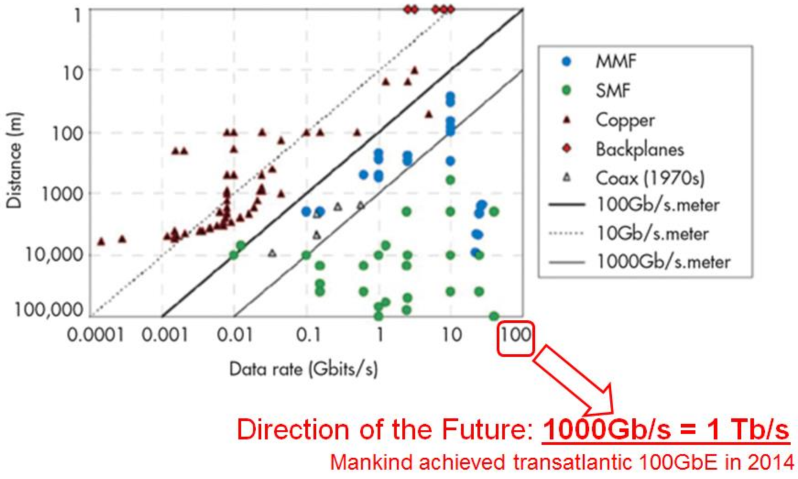


Figure 2.11: Technology Adoption Life-Cycle Analysis of Broadband Technology

Shown in Figure 2.11 above is the mapping of the current technology onto the Technology Adoption Life-Cycle [28], with the early adopters differentiated between five of the leading industry hardware manufactures and four of the leading industry service providers. We see that the 100Gb+ networks are forthcoming and being developed by the world's best hardware manufacturers and service providers.

2.1.5 Direction of the Future

As shown in Figure 2.12 below, mankind has already achieve a 100 Gb transatlantic connection.



Direction of the Future: 1000Gb/s = 1 Tb/s
Mankind achieved transatlantic 100GbE in 2014

Figure 2.12: Fiber-Optic Market Decomposition (Top View)
Source: [29]

The achievement of the transatlantic 100 Gb demonstrates that the technological progression of the fiber-optics is poised to further revolutionize the global telecommunications speeds by orders of magnitude.

2.1.6 The Zettabyte Era—Trends and Analysis

Shown in Figure 2.13 below is a forecast for global Internet Protocol (IP) traffic reaching 168 Exabyte's per month (2 x 10^{21} bytes per year) by 2019, growing at a 23% Compound Annual Growth Rate (CAGR).

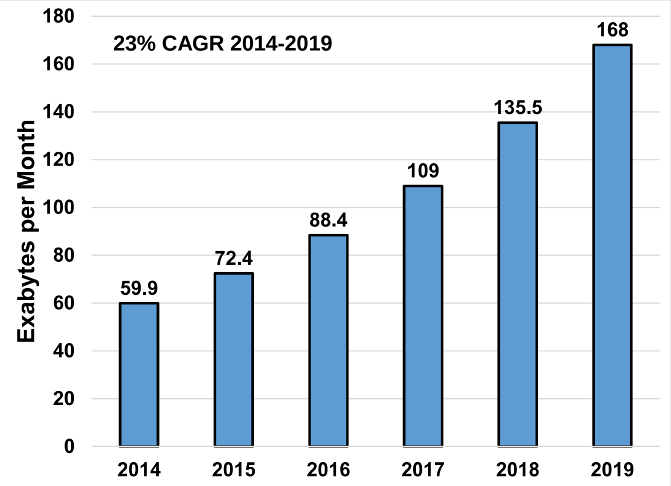


Figure 2.13: Cisco VNI Forecasts 168 Exabytes per Month of IP Traffic by 2019
Source: [30]

We see that the future is geared to reach speeds that are orders of magnitude larger than at the time of writing this work, and it will be driven by technology rooted in optical networking. This magnitude of IP traffic will all be enabled by fiber-optic networks infrastructure that is rooted within the data centers.

2.1.7 Summary of Market Analysis

The purpose of beginning this research with a market analysis was to establish the high level importance that data centers and optical networks play in our society. From this study, we draw four observations about the market analysis for data centers and fiber-optic network technology:

1. Provide a critical nexus of services to our national telecommunications infrastructure;
2. Have a positive and growing impact on the economy;
3. Creates differentiated platform services for new product offerings; and
4. Enables the future telecommunications to scale by orders of magnitude.

With these broad insights gained from the market study on data centers and fiber-optics networks, it is the motivation of this thesis to focus on considering data center design and focus on the optical networks.

In the next section, is a discussion about the the approach to considering a systems analysis of fiber-optic networks.

2.2 Fiber Optic Technology

Discussed below is theory leading to a discussion about computing optical transmission quality, Q-factor.

2.2.1 Optical Wave Theory

The premise of optical-fiber is that a transmitting (TX) light source (e.g., laser, LED) is emitted on one end of the fiber and that the lightwave, λ, travels through the material to reach the other side, at close to the speed of light, c, of approximately 2 x 10^8 m/s [56]. Fluctuating the light source in a pulse manner results in a binary communication that a receiver (RX) can translate into communication.

In the consideration of fiber-optic network systems design, there are five parameters and their optical wave theory, which are important to understand, and defined by [57]:

[1] **Mode-Field Diameter (MFD)**: Not all light that enters the optical fiber reaches the end receiver. The distribution of the light through the center core is referred to as "mode field". As shown in Figure 2.14, the MFD is a distribution of size of the power, with the greatest intensity in the center.

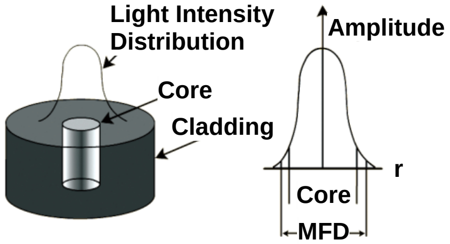


Figure 2.14: Mode-Field Distribution

[2] **Total Internal Reflections (TIR)**: As shown in Figure 2.15, light is propagated because the refractive index of the inner core, n_1, is greater than of the outer cladding, n_2.

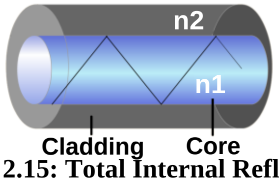


Figure 2.15: Total Internal Reflections

[3] **Numerical Aperture (NA)**: As shown in Figure 2.16, the lightwave must enter the optical-fiber through an aperture. The numerical aperture is a measure of acceptable angle that should minimize the refraction of light. The NA is defined by the refractive index of the cladding and core:

$$NA = Sin\, \theta = \sqrt{(n_2)^2 - (n_1)^2} \quad \textbf{(2.1)}$$

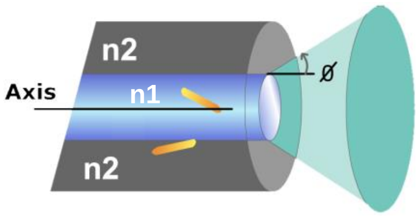


Figure 2.16: Numerical Aperture

[4] **Attenuation**: The reduction in signal power decibels (dB) is defined by a logarithm unit of measure of the ratio between output-to-input power. Each optical fiber has attenuation, measured in dB per kilometers (dB/km).

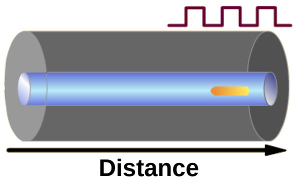


Figure 2.17: Attenuation

[5] **Dispersion**: The measurement of the spread of the light pulses from the fluctuating pulses is captured as Dispersion, which can cause bit errors and data loss. Mode conditioning or regenerating the signal can compensate for dispersion.

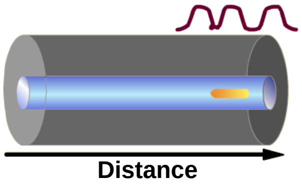


Figure 2.18: Dispersion

2.2.2 Optical Fiber Types

2.2.2.1 Overview

Shown in Figure 2.19 below, the manufacturing of optical-fiber consists of the three primary layers: an innermost core layer consisting of the optical fiber, the middle cladding layer which is typically a denser material than the optical fiber to cause refraction, and the outer most buffer layer which provides protection from the environment. Three main core layer sizes exist, represented by 9, 50, and 62.5, micro-meters (µm).

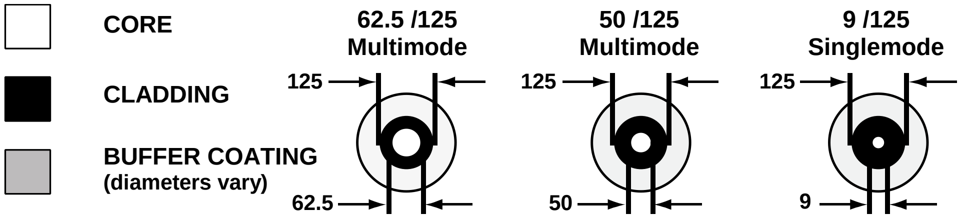
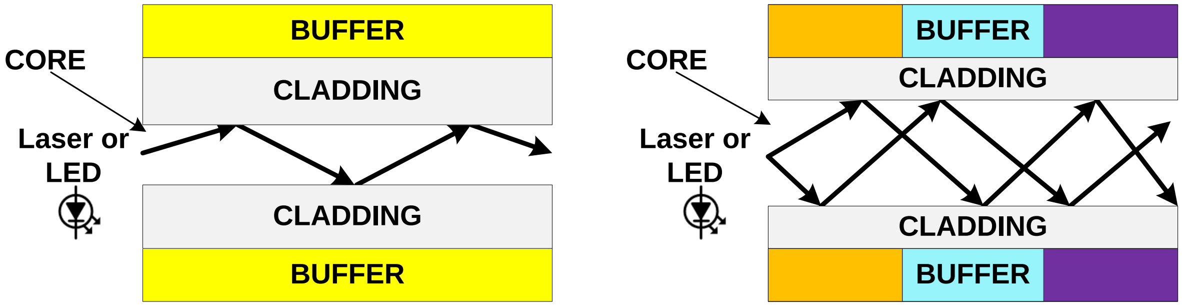


Figure 2.19: Comparison of Optical Fiber Cross-Sections
Source: [55]

Shown in Figure 2.20 below is a longitudinal cross-section comparing the generalized light path within single-mode (A) and multi-mode optical (B) fiber; in reality, the light-wave paths are non-linear.



(A) Single-Mode optical fiber **(B) Multi-Mode Optical Fiber**

Figure 2.20: Comparison of Optical Fiber Internal Light Travel Path

The smallest, 9/125µm, referred to as OS1, is used for single-mode communication, in which only one wavelength is passed in one direction. The 9/125µm single-mode optical fiber has a buffer color that is typically colored yellow. The 62.5/125µm, referred to as OM1, and 50/125µm, referred to as OM2, OM3 or OM4, are multi-mode fibers (MMF) which have a larger aperture diameter for the core and use "…parallel-optics transmission instead of serial transmission due to the 850-nm vertical-cavity surface-emitting laser (VCSEL) modulation limits at the time the guidance was developed." [36] The multi-mode fiber have a buffer layer that is typically colored orange for 62.5/125µm (OM1) and 50/125µm (OM2), aqua for 50/125µm (OM3) which is laser-optimized, supporting 10G, 40G, and 100G speeds, and purple for 50/125µm (OM4) is laser-optimized, supporting 10G, 40G and 100G speeds at longer distances.

In the next sections is a specific discussion about the single-mode and multi-mode optical-cables characteristics, as it pertains to: bandwidth, attenuation, 1 Gb, 10 Gb, 40 Gb, and 100 Gb data rate speeds.

2.2.2.2 Single-Mode

As shown in Table 2.2 below, the use of a single-mode fiber optic is designed for long range distance, typically measured in kilometers. “OS1 and OS2 are standard single-mode optical fiber used with wavelengths 1310 nm and 1550 nm [5] (size 9/125 µm) with a maximum attenuation of 1 dB/km (OS1) and .4 dB/km (OS2). OS1 is defined in ISO/IEC 11801 and OS2 is defined in ISO/IEC 24702.” [58] The typical use for the OS1 is for indoor solutions. The typical appropriate use for OS2 is for outdoor solutions.

Table 2.2: Single-Mode Fiber-Optic Characteristics
Source: [58] [68]

Category	Minimum modal bandwidth 1310 nm / 1550 nm	Maximum Attenuation	1Gb Ethernet 1000BASE-SX (max distance)	10Gb Ethernet 10GBASE-SR (max distance)	40 Gb Ethernet (max distance)	100 Gb Ethernet (max distance)
OS1 9/125		1 dB/km	2000 m		Not supported	Not supported
OS2 9/125		.4 db/km	5000 m	10000m (1310nm) 40000m (1550m)	10 km	10km (1310nm) 40km (1510nm)

2.2.2.3 Multi-Mode

The multi-mode optical optic is designed for the 850 nm / 1310 nm modal bandwidth, operating at the short distances, measured in meters, as shown in Table 2.3 below.

Table 2.3: Multi-Mode Fiber-Optic Characteristics
Source: [58] [68]

Category	Laser Optimized	Attenuation dBm/km	Minimum modal bandwidth 850 nm / 1310 nm	100 Mb Ethernet 100BASE-FX (max distance)	1Gb Ethernet 1000BASE-SX (max distance)	10Gb Ethernet 10GBASE-SR (max distance)	40 Gb Ethernet (max distance)	100 Gb Ethernet (max distance)
OM1 62.5/125	NO	3.5	200 / 500 MHz-km	2000 meters	275 meters	33 meters	Not supported	Not supported
OM2 50/125	NO	3.5	500/- MHz-km	2000 meters	550 meters	82 meters	Not supported	Not supported
OM3 50/125	YES	2.8	2000 MHz-km	2000 meters	550 meters	300 meters	100 meters 330 meters/ QSFP+eSR4	100 meters
OM4 50/125	YES	2	4700 MHz-km	2000 meters	1000 meters	550 meters	150 meters 550 meters/ QSFP+eSR4	150 meters

The categories are based on 62.5/125 µm (OM1) and the 50/125 µm (OM2, OM3, and OM4). Each fiber type category supports different frequencies, speeds, and maximum lengths.

2.2.3 Optical Bandwidth

Understanding the influence of the physical characteristics of the optical fiber on the propagation of optical light wavelength is vital to systems design planning. The measurement of how much data is transmitted along optical-fiber is referred to as bandwidth, which in simple terms, is a measure of "how square the input pulse remains ('0' and '1') and how far down the fiber." [37] Higher bandwidth is capable of preserving the transmitter pulses so the receiver is able to discern more of the state transitions between '0' and '1'.

To understand how to measure bandwidth, an understanding of: index type, modal delay, bit error rate (BER), and optical signal-to-noise ratio (OSNR) is discussed below:

2.2.3.1 Index Types

There are two index types which influence the refractive nature of optical fiber [37]: 1) Step and 2) Graded. The Step-index follows a uniform 'step-wise' decrease in refractive index from the axis. The Graded-Index (aka, Gradient-index), has a 'continuous' decreasing refractive index from the axis. The effect of the index type on bandwidth is that it causes light to travel in different paths, resulting in the different modes to arrive at the receiver at different time and leads to errors. This effect is referred to as Differential Modal Delay (DMD).

2.2.3.2 EMBc Methodology

"The superior method for measuring the bandwidth capability of an optical-fiber is the: Calculated Minimum Effective Bandwidth (EMBc). The EMBc proves the most trusted measure in the industry to ensure high performance operation as a standards compliant (TIA FOTP 22, IEC 60793-2-10 Ed 2.0) measurement." [37] The process compares the fibers over a broad range of testing, measuring at several VCSEL sources at the extremes of the available sources. Optical fiber that has passed EMBc testing will operate properly at the disclosed specifications.

2.2.3.3 Bit Error Rate (BER)

Optical system performance is characterized using the bit error rate (BER), which is the measurement of error bits received relative the number of good bits [78, Ch. 7.4.6]. For most optical-systems, the minimum error rate is 10^{-12}, with faster systems needing lower error rates.

2.2.3.4 Q-factor from OSNR

An important parameter in the design of optical networks is the Optical Signal to Noise Ratio (OSNR). From [79, pp. 222–223], [80, Sec. Appendix B] we gain an understanding that optical system performance is characterized using the minimum bit error rate (BER) by using a ratio of optical signal to noise estimation,

$$Q = \frac{|I_1 - I_0|}{\sigma_1 + \sigma_0} \tag{2.2}$$

in which I_1 and I_0 are the levels of the transmitted data of '1's and '0's, and the σ_1 and σ_0 are the standard deviations of the noise on of the '1's and '0's, respectively.

Furthermore, the BER is approximately related to Q as follows [79] :

$$\begin{aligned} BER &= \frac{1}{2} erfc \frac{Q}{\sqrt{2}} \\ &\approx \exp(-\frac{Q^2}{2})/Q\sqrt{2\pi} \end{aligned} \tag{2.3}$$

The relationship between BER and Q-Factor is illustrated in Figure 2.21 below.

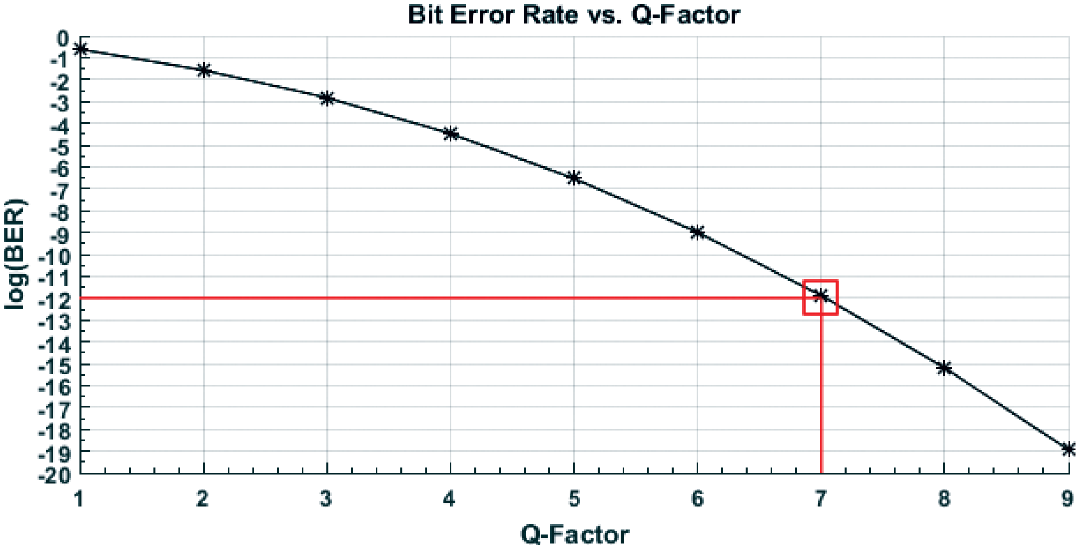


Figure 2.21: Bit Error Rate versus Q-factor

From [81, p. 7], we learn that the approximated measure of BER provides a simplified and valid approach to considering the BER. As noted by [82], [83, p. 95], optical systems operate with a guaranteed level of service defined by BER of 10^{-12}, or less.

This thesis bases the approach on achieving a minimum BER < 1e-12, which is Q-factor ≈ 7.

2.2.4 Optical Communication System

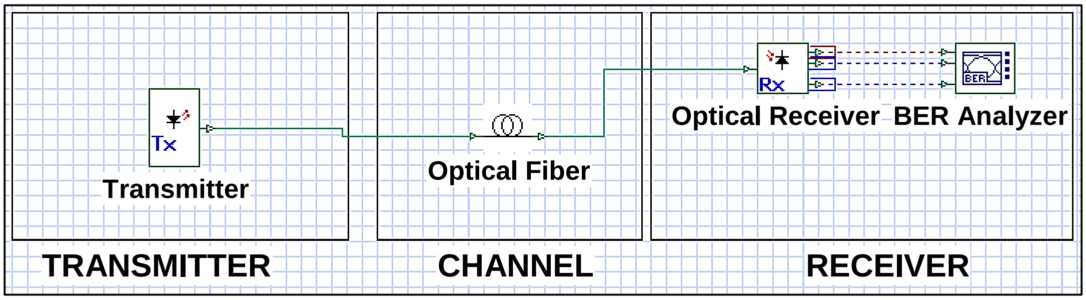


Figure 2.22: Fiber-Optic Communication System Design

Shown in Figure 2.22 above is a representation of the essential components in an optical network system consisting of a transmitter (TX), the channel consisting of the optical fiber, and the receiver (RX). An optical BER analyzer is attached onto the receiver to monitor the quality of the signal and facilitate optimizing the downstream adjustments.

2.2.4.1 Transmitters

Shown in Figure 2.23 below, the transmitter has five fundamental components: 1) Bit sequence generator, 2) Pulse Generator, 3) Filter, 4) Modulator, and 5) Laser.

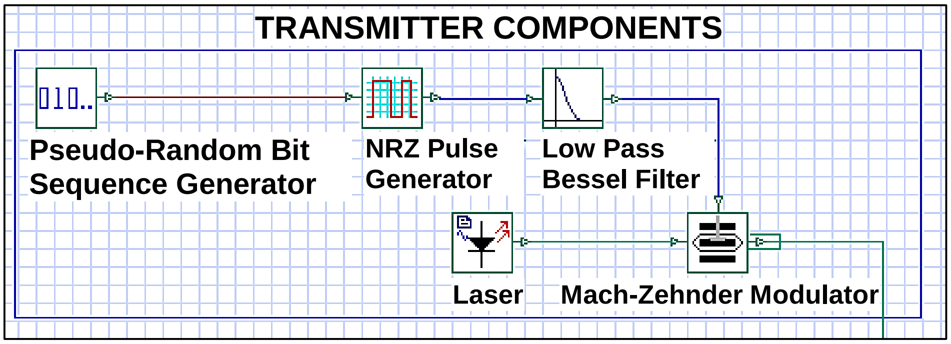


Figure 2.23: Transmitter Components

The bit sequence generator feeds into the pulse generator, which may have a filter applied, then the pulse is fed into a modulator to control the signal. The laser the powers the modulator signal into the optical fiber (channel).

2.2.4.2 Receivers

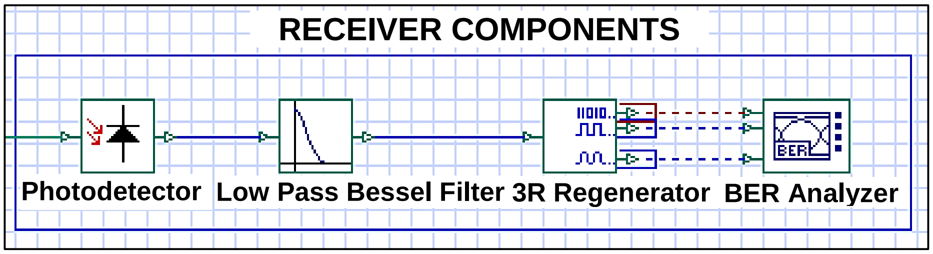
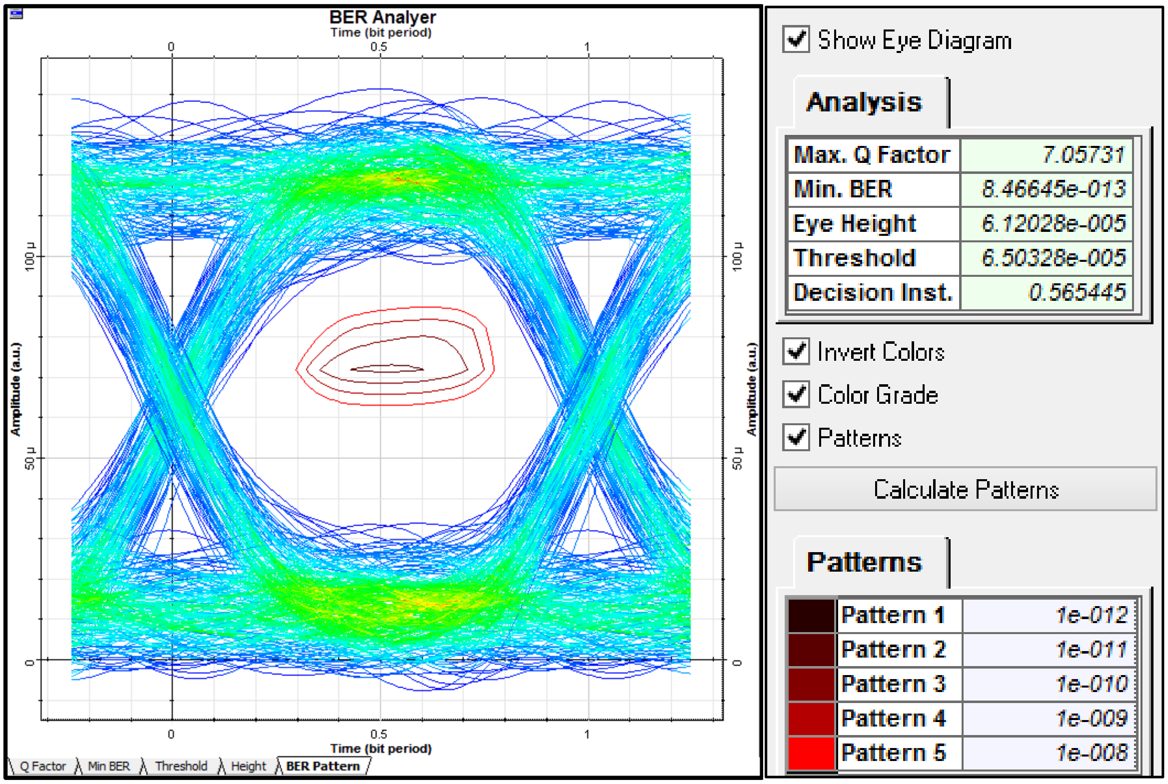


Figure 2.24: Receiver Components

The receiver consists of a photo-detector, of which there are two options, Intrinsic Photodiode (PIN) and Avalanche Photodiode (ADP); each has different attributes for detection and signal amplification that may be considered. To measure the signal requires passing through a low pass filter and into an electrical 3R Regenerator, which is coupled to a BER Analyzer.

2.2.4.3 Bit Error Rate (BER) Analysis



☑ Show Eye Diagram

Analysis

Max. Q Factor	7.05731
Min. BER	8.46645e-013
Eye Height	6.12028e-005
Threshold	6.50328e-005
Decision Inst.	0.565445

☑ Invert Colors

☑ Color Grade

☑ Patterns

Patterns

■	Pattern 1	1e-012
■	Pattern 2	1e-011
■	Pattern 3	1e-010
■	Pattern 4	1e-009
■	Pattern 5	1e-008

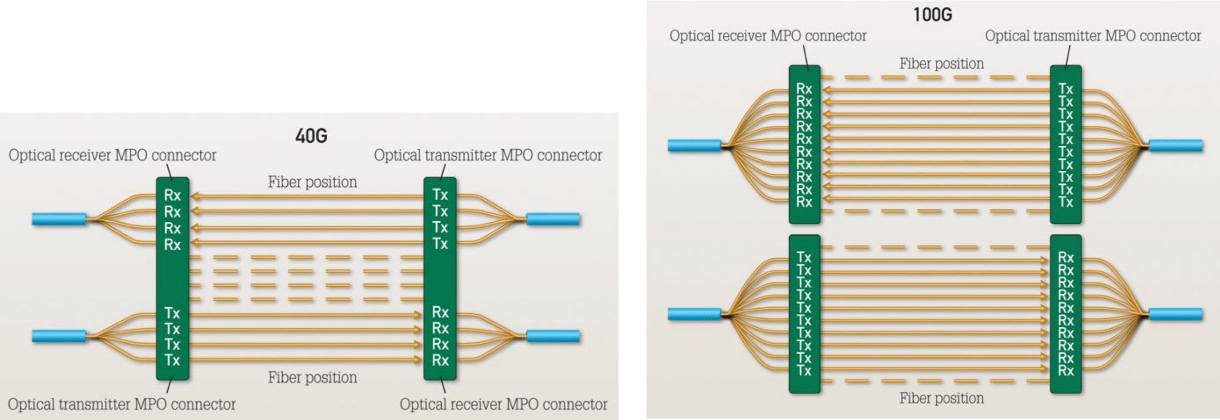
Figure 2.25: Bit Error Rate (BER) Analyzer at Q ≈ 7

Shown in Figure 2.25 above is an example of a BER analysis illustrating a Q-factor ≈ 7, BER < 1e-012, and the iso-performance BER patterns for five gradient levels of BER from 1e-012 to 1-008 within the eye-chart of a well-formed multi-mode signal.

2.2.5 Parallel Optics

In order to achieve transmission beyond 10G, technology has been developed that utilizes parallel optical signals, Figure 2.26 below, between the transceivers and the receiver [49]. In this work, I consider three forms:

- **10G = 1 x 10G**
- **40G = 4 x 10G**
- **100G = 10 x 10G**



4 x 10G 10 x 10G

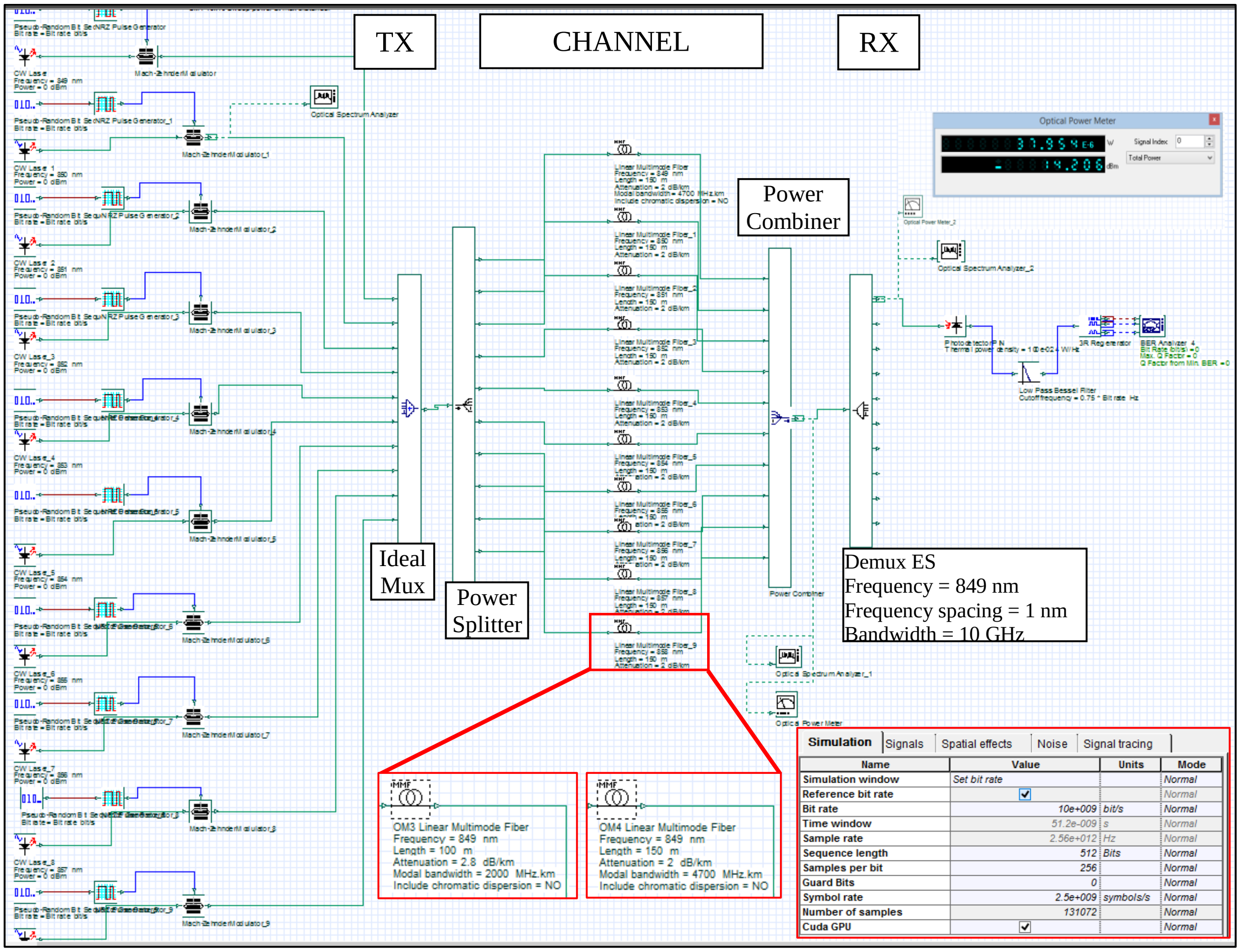
Figure 2.26: 40G and 100G Parallel Optics
Image Source: [40]

To gain an understanding of the parallel optical performance, two experiments are developed. The goal is to understand the relationship between TX power, optical fiber length, and RX sensitivity, with an intended outcome of a set of equations that represent the relationship.

The first experiment evaluates the Q-factor when sweeping the power at the max distance. The second experiment evaluates the relationship between Q-factor and sweeping the fiber length, with the TX power fixed at the optimized power setting of the max distance, as determined from experiment 1.

2.2.5.1 Experiments Framework

The experiments are conducted using OptiSystem 14, Figure 2.27 below, to emulate the 1 x 10G, 4 x 10G and 10 x 10G parallel configuration. The simulation was set at a Bit Rate of 10e+009 bits/s, Sequence Length of 512 bits, Samples per Bit of 256, and the CUDA GPU enabled.



Optical Power Meter: 37.954 E-6 W; -14.206 dBm; Signal Index 0; Total Power

Demux ES
Frequency = 849 nm
Frequency spacing = 1 nm
Bandwidth = 10 GHz

OM3 Linear Multimode Fiber
Frequency = 849 nm
Length = 100 m
Attenuation = 2.8 dB/km
Modal bandwidth = 2000 MHz.km
Include chromatic dispersion = NO

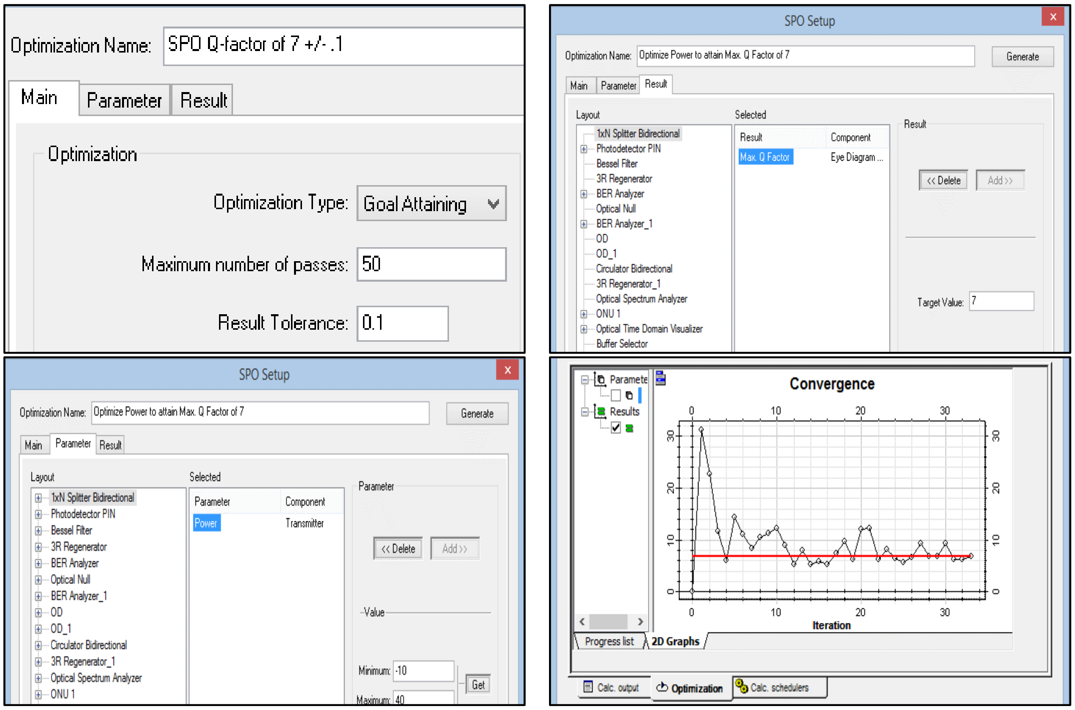
OM4 Linear Multimode Fiber
Frequency = 849 nm
Length = 150 m
Attenuation = 2 dB/km
Modal bandwidth = 4700 MHz.km
Include chromatic dispersion = NO

Name	Value	Units	Mode
Simulation window	Set bit rate		Normal
Reference bit rate	☑		Normal
Bit rate	10e+009	bit/s	Normal
Time window	51.2e-009	s	Normal
Sample rate	2.56e+012	Hz	Normal
Sequence length	512	Bits	Normal
Samples per bit	256		Normal
Guard Bits	0		Normal
Symbol rate	2.5e+009	symbols/s	Normal
Number of samples	131072		Normal
Cuda GPU	☑		Normal

Figure 2.27: Framework for Parallel Optics Experiments

The configuration has 10 transceivers (TX) set to 849 nm with 1 nm increments, each configured into the Ideal Mux, Splitter, Linear Multi-mode Fiber at the corresponding optical spectrum as the transceiver, Combiner, and Demux ES configuration to emulate parallel optics transmission. There is one receiver (RX) to measure performance with a BER analyzer, though in reality there would be one RX for each TX. However, for speed of simulation, one was utilized. The Bandwidth on the Demux is set at 10 GHz, starting at 849 nm with 1 nm spacing. The Receiver Photodetector PIN Thermal Power Density is set at 100e-024 W/Hz. Optical Power Meters are enabled to collect power measurements. The OM3 fiber was configured at 2.8 dB/km, modal bandwidth of 2000 MHz.km, and max distance of 100 meters. The OM4 fiber was configured at 2 dB/km, modal bandwidth of 4700 MHz.km, and max distance of 150 meters. In the 1 x 10G simulation, only 1 transceiver was enabled, in the 4 x 10G simulation, four transceivers were enabled, and in the 10 x 10G simulation all ten transceivers are enabled.

Utilizing the *Parameter Sweeps* and *Single-Parameter Optimization* (SPO) features of Optisystem, iterative optimization was performed towards goal attaining values. The SPO is used to perform an analysis for goal attaining Q-factor=7±.1 by sweeping power and sweeping distance. Shown in Figure 2.28 below is an example of one such experiment, illustrating the convergence of the result to Q-factor =7:

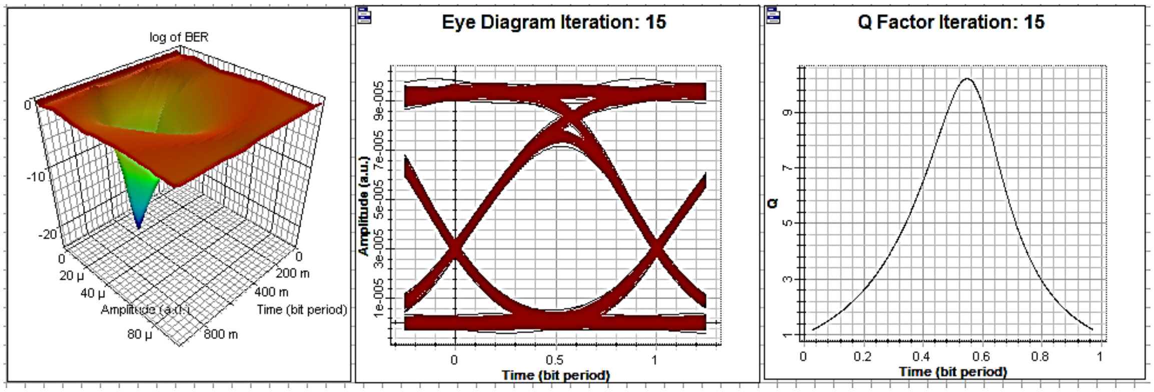

Optimization Name: SPO Q-factor of 7 +/- .1
Optimization Type: Goal Attaining
Maximum number of passes: 50
Result Tolerance: 0.1

SPO Setup
Optimization Name: Optimize Power to attain Max. Q Factor of 7
Selected: Result: Max. Q Factor; Component: Eye Diagram ...
Target Value: 7

SPO Setup
Optimization Name: Optimize Power to attain Max. Q Factor of 7
Selected: Parameter: Power; Component: Transmitter
Minimum: -10
Maximum: 40

Figure 2.28: OptiSystem Single-Parameter Optimization (SPO) to Q-factor= 7±.1

Lastly, the output of the simulations is collected utilizing the built-in report generator, which facilitates visualizations, such as Figure 2.29 below, and export of the data to MATLAB compatible formats.



3D BER Patterns Eye-Chart Q-factor

Figure 2.29: Example of OptiSystem Visualization Report Output

2.2.5.2 Power vs. Length

The procedure for the Power versus Length experiment is:

Step 1: Sweep a power range for the OM3 and OM4 at the maximum distance.

Step 2: Plot the Power versus the Q-factor in MATLAB.

Step 3: Determine the coefficients of the best-fit line, using a two-factor exponential fitting in MATLAB:

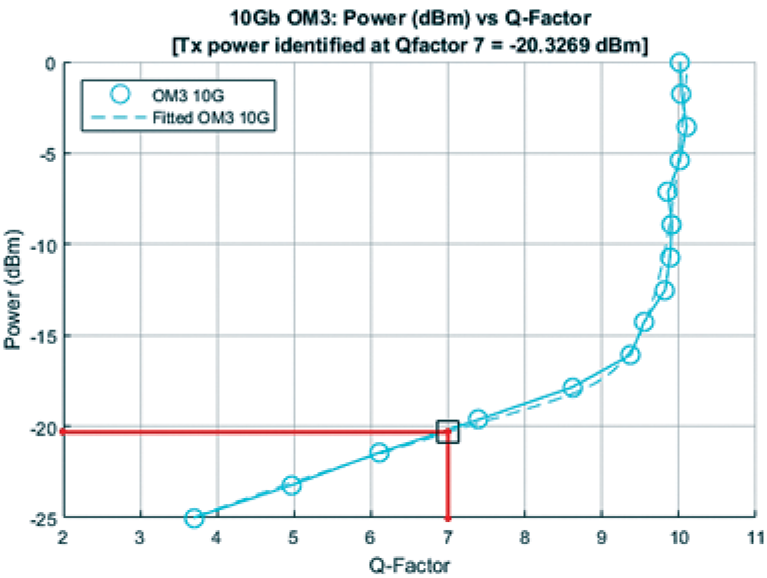
$$y = a * exp(b * x) + c * exp(d * x) \tag{2.4}$$

Step 4: Solve using the equation of the fitted line to determine the power at Q-factor = 7.

2.2.5.2.1 10G = 1 x 10 Gbps

In Figure 2.30 and Figure 2.31 below are the results of the Steps 1 – 4.

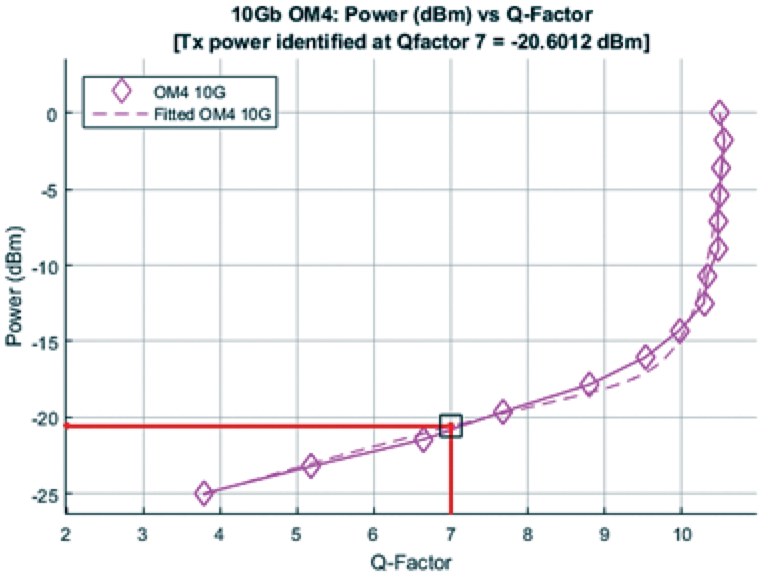
OM3



Q-factor = 7 determined at -20.3269 dBm

Figure 2.30: 10G OM3: Power (dBm) versus Q-factor

OM4



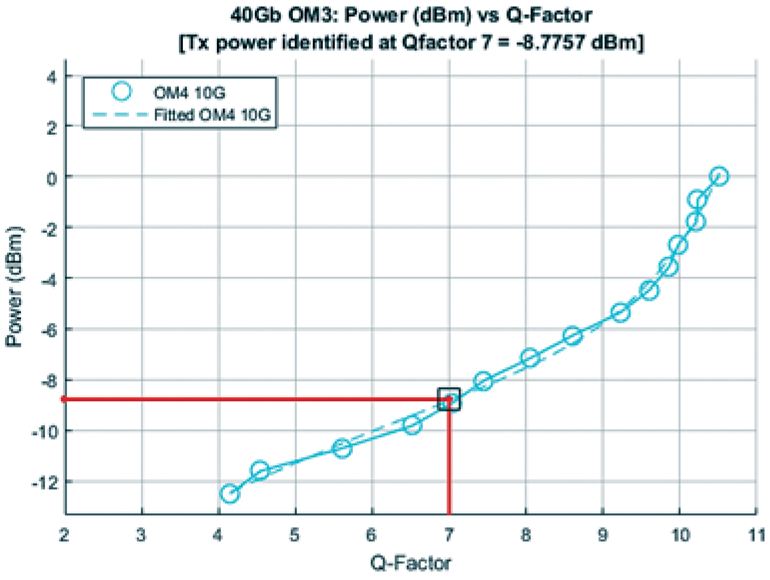
Q-factor = 7 determined at -20.6012 dBm

Figure 2.31: 10G OM4: Power (dBm) versus Q-factor

2.2.5.2.2 40G = 4 x 10 Gpbs

In Figure 2.32 and Figure 2.33 below are the results of the Steps 1 – 4.

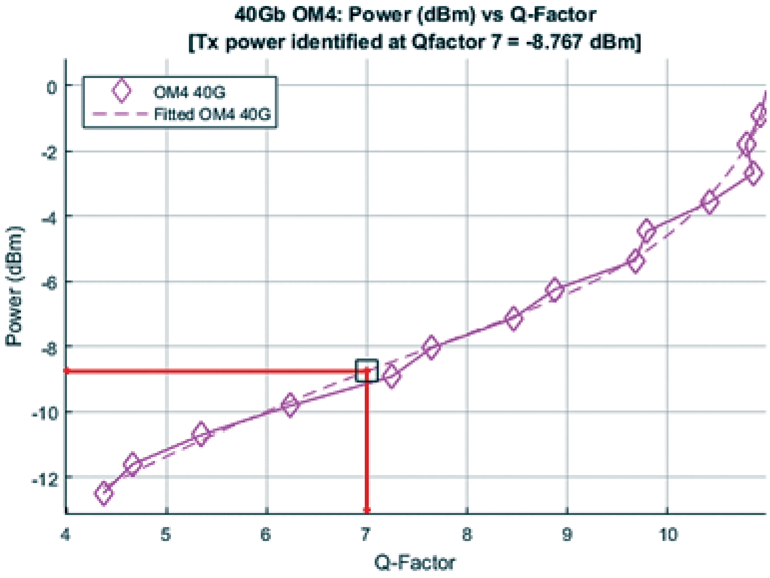
OM3



Q-factor = 7 determined at -8.7757 dBm

Figure 2.32: 40G OM3: Power (dBm) versus Q-factor

OM4



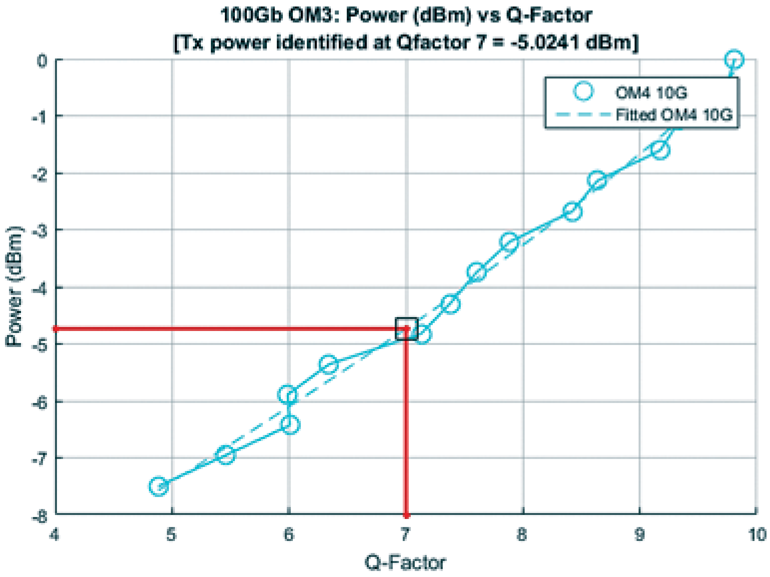
Q-factor = 7 determined at -8.767 dBm

Figure 2.33: 40G OM4: Power (dBm) versus Q-factor

2.2.5.2.3 100G = 10 x 10 Gpbs

In Figure 2.34 and Figure 2.35 below are the results of the Steps 1 – 4.

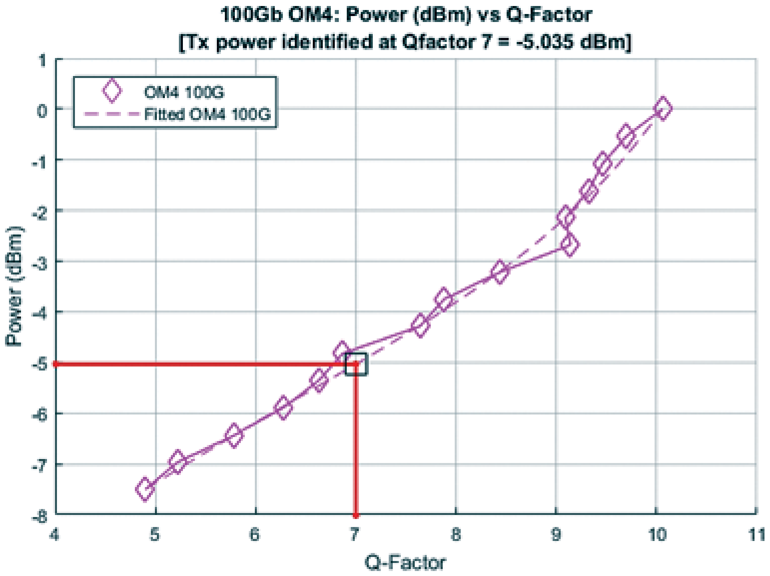
OM3



Q-factor = 7 determined at -5.0241 dBm

Figure 2.34: 100G OM3: Power (dBm) versus Q-factor

OM4



Q-factor=7 determined at -5.035 dBm

Figure 2.35: 100G OM4: Power (dBm) versus Q-Factor

2.2.5.2.4 Summary of Power vs. Length experiments

Table 2.4: OM3 vs. OM4: Power at Max Distance, Optimized for Q = 7

	OM3	**OM4**
10 Gbps	-20.3269 dBm	-20.6012 dBm
40 Gbps	-8.7757 dBm	-8.767 dBm
100 Gbps	-5.0241 dBm	-5.035 dBm

From the first set of experiments, we observe in the summary Table 2.4 above that the power requirements for OM4 and OM3 are nearly similar. We also observe that the incremental power requirements for 10G to 40G to 100G are substantial.

2.2.5.3 Q-factor vs. Length

Extending the procedure, these experiments now utilized the Single-Parameter Optimization (SPO) within OptiSystem to automatically determine the Power at the TX to yield Q = 7 through an iterative optimization. In these experiments, OptiSystem was utilized to optimize the power at the maximum distance, then that value was fixed and the length was swept using the power.

2.2.5.3.1 10G = 1 x 10 Gbps

Step 1: OM4 SPO at max distance for 1 x 10G.

	Max Distance	Attenuation	Modal Bandwidth	SPO determined Power at Tx to yield Q = 7
OM4	550	2 dBm/km	4700 MHz.km	-20.5 dBm

Step 2: Then sweep from 2 to 550 meters at -20.5 dBm. Save results to MATLAB.

Step 3: OM3 SPO at max distance for 1 x 10G

	Max Distance	Attenuation	Modal Bandwidth	SPO determined Power at Tx to yield Q = 7
OM3	300	2.8 dBm/km	2000 MHz.km	-20.45 dBm

Step 4: Sweep from 2 to 300 at -20.45 dBm. Save results to MATLAB.

Step 5: Determine and plot the fitted equations using two-term exponential format.

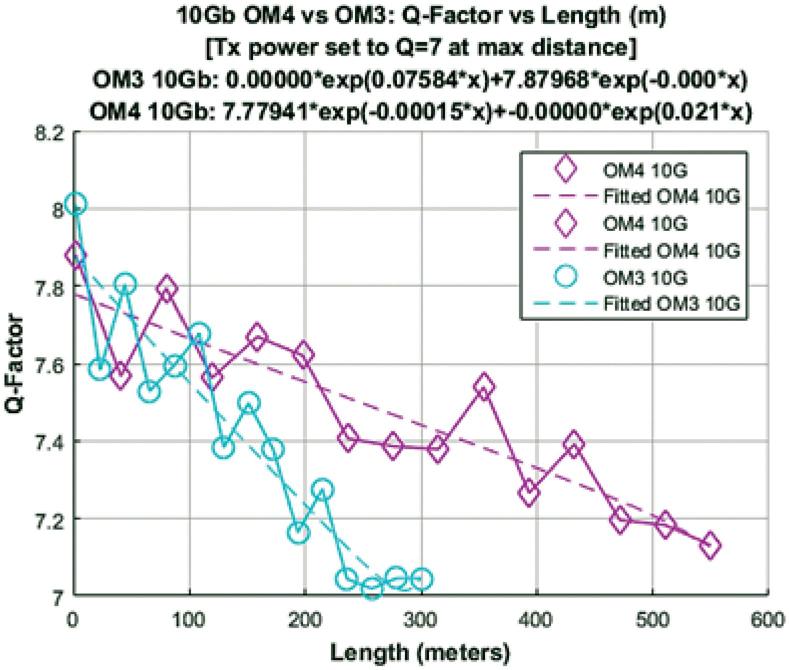


Figure 2.36: 10G OM4 vs. OM3: Q-factor versus Length

From Figure 2.36 above, we observe that the OM4 is outperforming the OM3 at longer distances.

2.2.5.3.2 40G = 4 x 10 Gbps

Step 1: OM4 SPO at max distance for 4 x 10G.

	Max Distance	Attenuation	Modal Bandwidth	SPO determined Power at TX to yield Q = 7
OM4	150	2 dBm/km	4700 MHz.km	-8.9765625 dBm

Step 2: Then sweep from 2 to 550 meters at -8.9765625 dBm. Save results to MATLAB.

Step 3: OM3 SPO at max distance for 4 x 10G

	Max Distance	Attenuation	Modal Bandwidth	SPO determined Power at TX to yield Q=7
OM3	100	2.8 dBm/km	2000 MHz.km	-9 dBm

Step 4: Sweep from 2 to 300 at -9 dBm. Save results to MATLAB.

Step 5: Determined and plot the fitted equations using two-term exponential format.

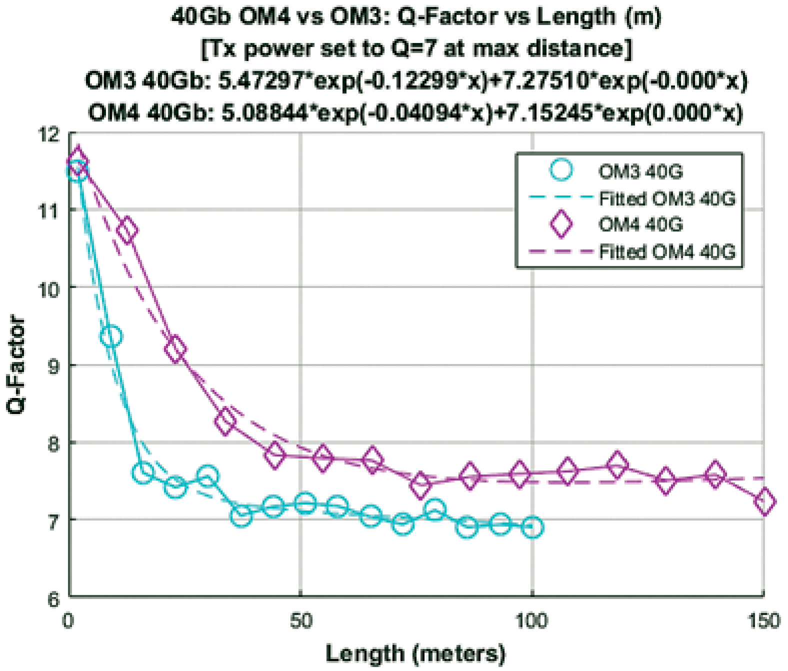


Figure 2.37: 40G OM4 vs. OM3: Q-factor versus Length

From Figure 2.37 above, we observe that the OM4 is outperforming the OM3.

2.2.5.3.3 100G = 10 x 10 Gbps

Step 1: OM4 SPO at max distance for 10 x 10G.

	Max Distance	Attenuation	Modal Bandwidth	SPO determined Power at Tx to yield Q=7
OM4	150	2 dBm/km	4700 MHz.km	-5.0 dBm

Step 2: Then sweep from 2 to 150 meters at -5.0 dBm. Save results to MATLAB.

Step 3: OM3 SPO at max distance for 10 x 10G

	Max Distance	Attenuation	Modal Bandwidth	SPO determined Power at Tx to yield Q=7
OM3	100	2.8 dBm/km	2000 MHz.km	-5.05 dBm

Step 4: Sweep from 2 to 100 at -5.05 dBm. Save results to MATLAB.

Step 5: Determined and plot the fitted equations using two-term exponential format.

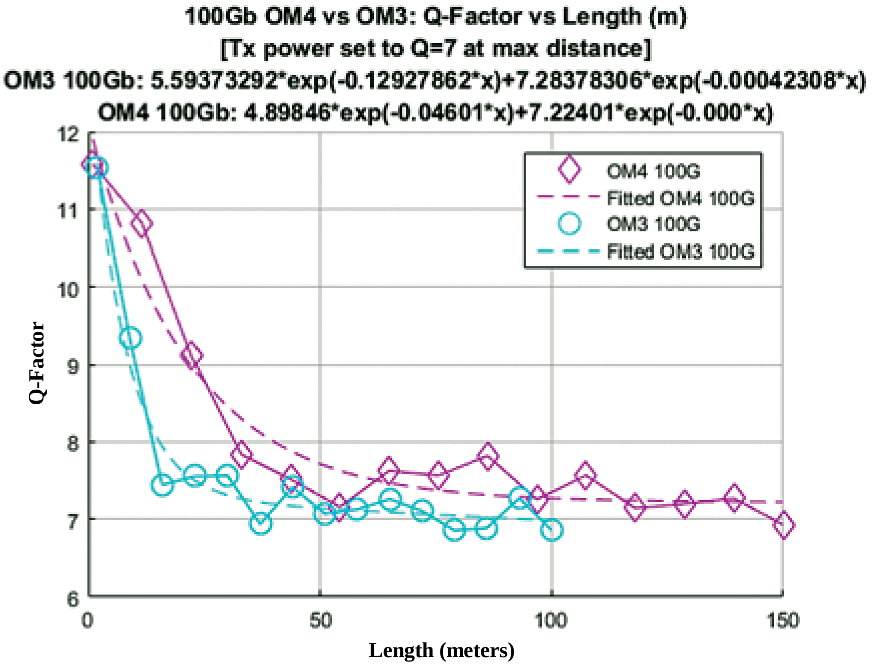


Figure 2.38: 100G OM4 vs. OM3: Q-factor versus Length

From Figure 2.38, we observe that the OM4 is outperforming the OM3.

2.2.5.3.4 Summary of Q-factor vs Length experiments

In Table 2.5 and Table 2.6 are presented the results of the parallel optics experiments.

Table 2.5 OM3: Equations for Q-factor vs. Length (TX Power (dBm) Q = 7 ± .1 at Max Distance)

	(A) Power Fitted Eqn. Q=7.0	(B) Power SPO Optimized Q=7 ± .1	(C) Δ	(D) Eqn. Based on SPO (automated)	
10G*	-20.3269	-20.45	.6%	y = 7.37968.*exp(-.000215)	(2.5)
40G	-8.7757	-9	2.6%	y = 5.47297*exp(-0.12299*x)+7.27510*exp(-0.0004*x)	(2.6)
100G	-5.0241	-5.05	.5%	y = 5.59373292*exp(-0.12927862*x)+7.28378306*exp(-0.00042308*x)	(2.7)

*10G was fitted using 1-term exponential

Table 2.6: OM4: Equations for Q-factor vs. Length (TX Power (dBm) Q = 7 ± .1 at Max Distance)

	(A) Power (dBm) Fitted Eqn. Q=7.0	(B) Power (dBm) SPO Optimized Q=7 ± .1	(C) Δ	(D) Eqn. Based on SPO (automated)	
10G	-20.6012	-20.5	.6%	y=7.77941*exp(-0.00015*x)+-0.000001*exp(0.021*x)	(2.8)
40G	-8.767	-8.9765625	2.4%	y=5.08844*exp(-0.04094*x)+7.15245*exp(0.00001*x)	(2.9)
100G	-5.035	-5.0	.5%	y=4.89846*exp(-0.04601*x)+7.22401*exp(0.0001*x)	(2.10)

In Column A, the Power (dBm) fitted values were computed analytically by plotting the sweep of the power settings in MATLAB, solving for the coefficients of the best-fit of the line using a two-term exponential equation, and then solving for the power at Q=7 using the equation of the best-fit line. Column B represents the results from an alternative approach that utilized the Single-Parameter Optimization (SPO) features of Optisystem, which automatically solved for the optimal power at Q-factor = 7 ± .1. Thus, in this work are demonstrated two approaches: first is the approach to determine the Q-factor analytically, and, secondly is the approach for utilizing an automated simulation approach. Column C represents the delta difference (%) between the two approaches. Column D provides the resulting equation of Q-factor vs Length, based on the SPO optimization approach. The automated SPO approach was used primarily because the results are close to the more time-consuming analytical approach. The equations in Column D were the goal of the experiments, and as such, will be utilized in the system design optimization when evaluating the trade-offs of optical quality and distance within the design options.

2.2.6 Summary of Fiber Optic Technology

In summary, we draw several observations about fiber-optic technology:

1. Optical wavelengths can be focused in glass fibers to span short and long distances;
2. The performance of the optical bandwidth is determined using the measurement for the *Calculated Effective Modal Bandwidth (EMBc)*;
3. The optical communication design requires a transmitter (TX), channel, and receiver (RX). A BER analyzer can be attached on the optical receiver to observe and optimize the Q-factor;
4. The quality of the optical signal at the receiver (RX) can be measured with a Q-factor value, with a Q-factor ≈ 7 representing a Bit Error Rate = 1e-12 which is the minimum value for guaranteed optical performance. The Q-factor is the Dual of the BER, meaning the optimization can be either to minimize the BER, or, maximize the Q-factor;
5. Parallel optical channels enables transmission of 10G (1 x 10 Gbps), 40G (4 x 10 Gbps), and 100G (10 x 10 Gbps). The future innovations of optical-networks will rely on parallelism;
6. A target Q-factor can be discovered by sweeping power settings and utilizing a two-term exponential fitting to determine the coefficients of the best-fit equation. Then using this equation, it is possible to analytically solve for the target values;
7. Utilizing the OptiSystem simulation Single-Parameter Optimization (SPO) features can rapidly compute the optimal power through automated simulation; and
8. The fitted equations of Power vs Length in Columns D of Table 2.5 and Table 2.6 above are generated from theoretical experimentation of OM3 and OM4 multi-mode optical fiber at 10G, 40G, and 100G. These equations are used in the multi-objective fiber-optic system design optimizations.

In the next section 2.3 is a discussion about data centers.

2.3 Data Center

2.3.1 Facilities

Shown in Figure 2.40 below is a representation of the main components of a data center which is useful to understand the complexity of the infrastructure and will be important in the design of the network and power requirements to operate the facility:

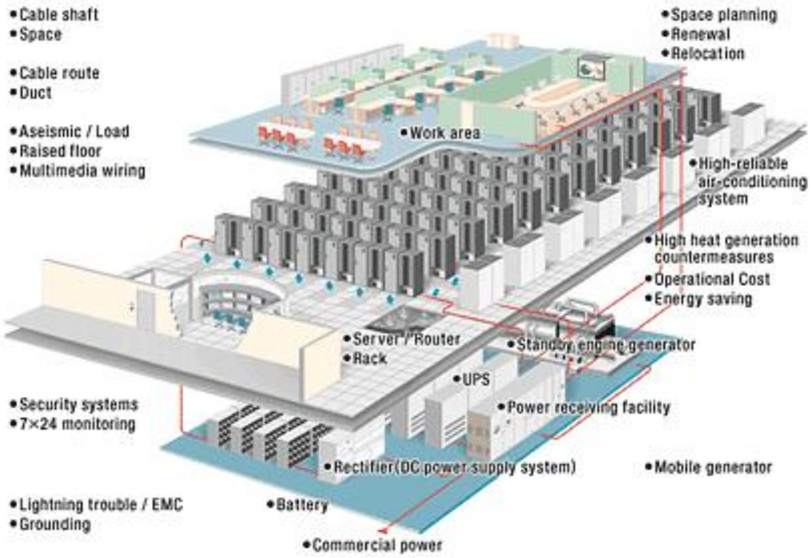


Figure 2.39: Generic Data Center Facilities Diagram
Source: [47]

The data center facility contains multiple areas of operations, as summarized in Table 2.7 below:

Table 2.7: Summary of Data Center Infrastructure Components

- Work Area/Office Spaces
- Space Planning/Relocation Area
- High-reliable air conditioning system
- High head generation countermeasures
- Standby-generators
- Uninterrupted Power Supply (UPS)
- Cable Route/Ducts
- Servers/Router Rack
- Networking cables
- DC Power Supply System
- Battery
- Commercial Power
- Lightning trouble/EMC
- Grounding
- Security System
- 7x24 monitoring
- Aseismic counter measures
- Raised Floors
- Overhead raceways
- Mobile Generators
- Power Receiving Facility
- Loading dock facility

2.3.2 Segmented Floor Plan

Shown in Figure 2.40 below is a generalized data center fiber-optic network, illustrating the standard's based division of three areas: Entrance, Main Distribution, and Horizontal Distribution Area.

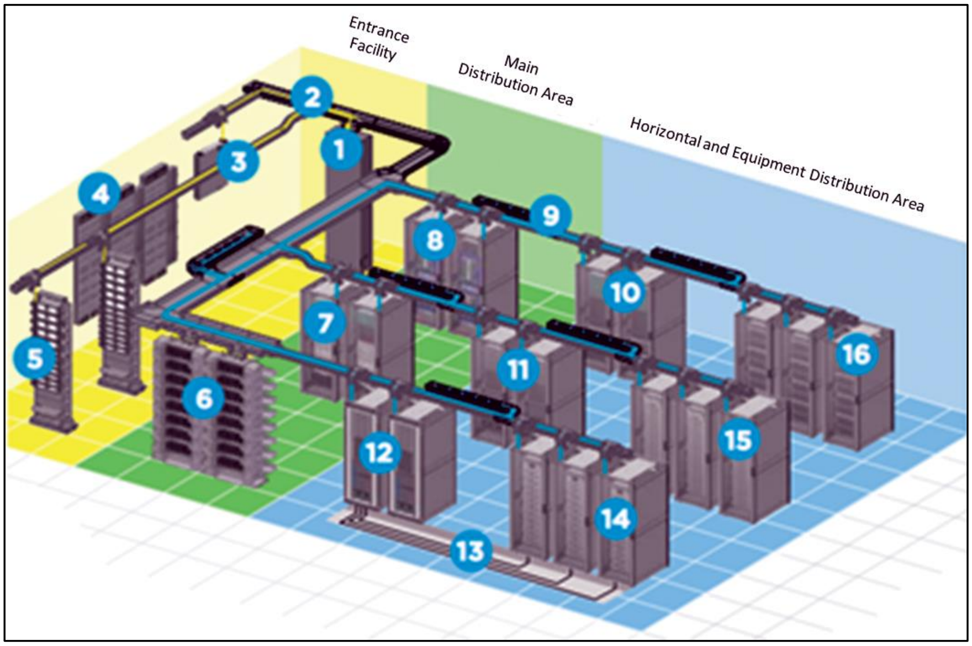


Figure 2.40: Generic Representation of a Data Center Floor Plan
Source: [48]

The optical network components for each area are defined in Table 2.8 below:

Table 2.8: Optical Components in a Data Center Floor Plan

Section	#	Name	Purpose
Entrance Facility	1	Splice Frame	Organizing optical fiber
	2	Optical Raceway	Organizing fiber overhead
	3	Termination/Splice Fiber Panel	Splicing fiber
	4	Termination Blocks	Terminating connection's
	5	Termination/Splice Fiber Panel	Splicing/Terminating
Main Distribution Area (MDA)	6	Optical Distribution Frame	Backbone interconnections
	7	High-Density Fiber Panel	Interconnections of optical cable
	8	Storage Area	Vertical blade SAN directors
	9	Pre-terminated Fiber Optic Cabling	Intra-connections
Horizontal And Equipment Distribution Area (HDA)	9	Raceway	Fiber-Optic multi-mode
	10	Angle Left/Right Fiber Panel	Cassettes for easy access to ports.
	11	Universal Connectivity Platform	Enables mix of fiber and cooper cabling
	12	Pre-terminated Copper Solutions	Factory testing cooper cables
	13	Copper Cabling	Horizontal cabling
	14	Copper Patch Panels	Connecting copper
	15	Direct Attach Cabled (DAC)	Passive and active copper
	16	Fiber Patch Panels	Patching and splicing

2.3.3 Data Center Design Considerations

There are four data center design considerations that are relevant to this thesis work: 1) Tiered Service Levels, 2) Power Usage Effectiveness (PUE), 3) Power Cost Modeling, and 4) Economics of TOR vs EOR.

2.3.3.1 Tiered Service Levels

In Figure 2.41 below is shown the TIA-942 standard for redundant data center topology.

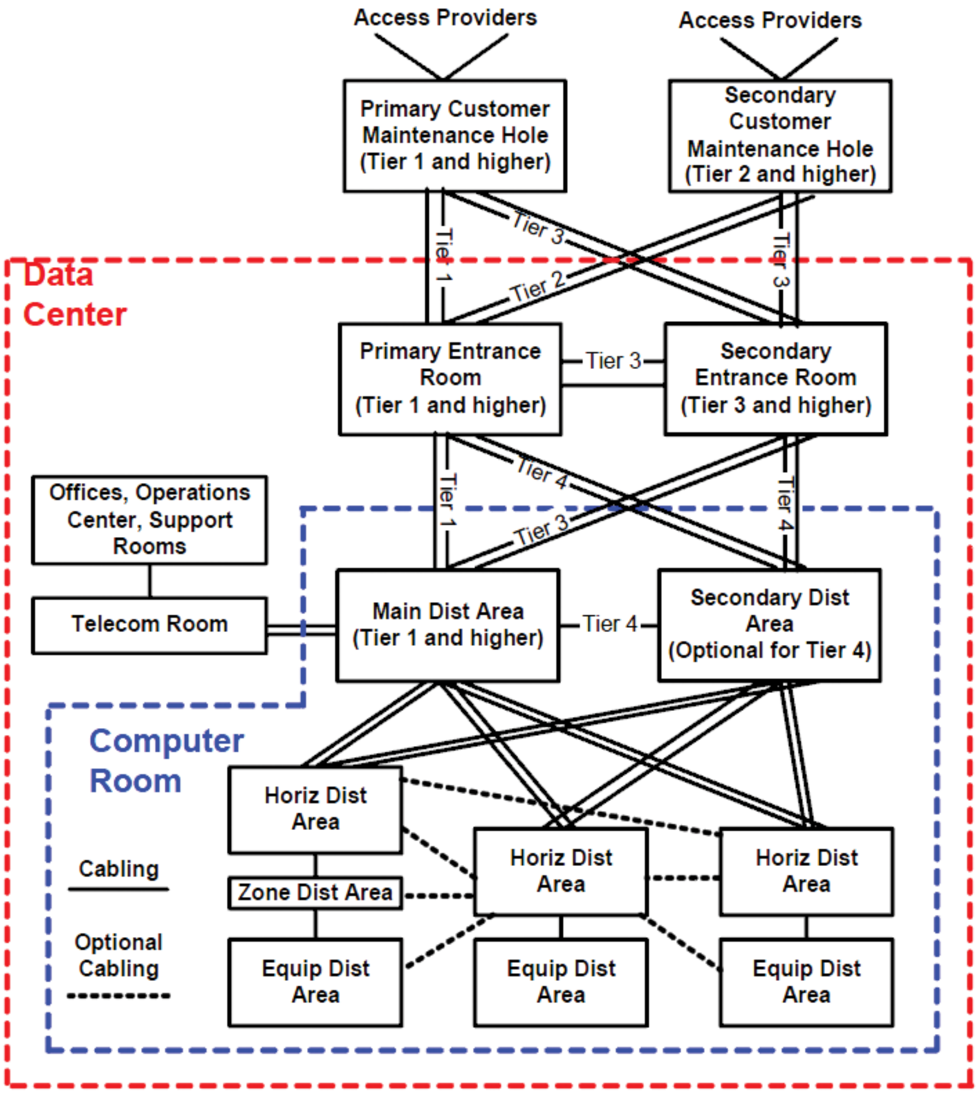


Figure 2.41: TIA-942 Data Center Infrastructure Redundancy Topology
Source: [15]

Based on the redundant infrastructure levels, Table 2.9 below, data centers are certified into one of four tiers levels [39]. The tiered service level is increased through redundancy of infrastructure that minimizes the annual downtime.

Table 2.9: Data Center Redundancy Tier Levels
Sources: [70]–[72]

LEVEL	Tier 1 Basic Site	Tier 2 Redundant	Tier 3 Concurrently Maintainable	Tier 4 Fault Tolerant
SCOPE	[1] Single path for power/cooling distribution [2] No redundant components	[1] Single path for power/cooling distribution [2] Redundant components	[1] Multiple power/ cooling distribution-- one path active [2] Redundant components [3] Concurrently maintainable	[1] Multiple active power/cooling paths [2] Redundant components [3] Fault tolerant
DOWNTIME	<28.8 hr/yr	< 22.0 hrs/yr	< 1.6 hrs/yr	<.4 hrs/yr
UPTIME	99.671%	99.749%	99.928%	99.995%
DELIVERY PATHS	1	1	1 Active, 1 Passive	2 Active
REDUNDANCY	NO	N+1	N+1	S+S, or 2(N+1)
COMPARTMENT-ALIZATION	NO	NO	NO	YES
CONCURRENTLY MAINTAINABLE	NO	NO	YES	YES
FAULT TOLERANT TO WORST EVENTS	NO	NO	NO	YES

Due to the financial cost of each escalating tier there are limited Tier 4 facilities. Only two US facilities are currently Tier IV Gold certified: one in Las Vegas, NV and the second in Olathe, KS [39].

2.3.3.2 Power Usage Effectiveness (PUE)

The most common metric used to express the power efficiency in data centers is defined by [54]:

$$PUE = \frac{\text{Total power consumed by a datacenter}}{\text{Power consumed by servers}} \tag{2.11}$$

The ratio value of 1.0 is the lowest value that can be attained for Equation 2.11 above. Shown in Figure 2.42 below is an example of the power consumption from a data center power utilization study [54].

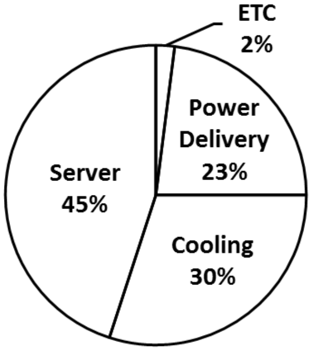


Figure 2.42: A Breakdown of Datacenter Energy Overhead Costs
Source: [54, p. 863]

The managers of data centers have to consider the PUE value because it summarizes the costs that drive the operations of the facility. The study of environmental cooling is a significant area of importance in data center research. This work takes into consideration the PUE towards the life-cycle cost management.

2.3.3.3 Power Cost Modeling

The equations 2.12 - 2.18 below are adapted from [84] for power cost modeling:

Nomenclature:

Rate ≜ Annual cost of money
Facility_Amortize_Periods ≜ Years for amortization
Cost_of_Facility ≜ Total cost of the facility
Infrastructure ≜ Monthly cost of the amortized facility
Num_Servers ≜ Quantity
Cost_Per_Server ≜ Total cost
Server_Amortize_Periods ≜ Years for amortization
Servers ≜ Monthly cost of the amortized servers
Power_Cooling_Infrastructure Percentage ≜ Power cooling of infrastructure as percentage
Power_Cooling_Infrastructure ≜ Power cooling of infrastructure as dollars
Mega_WattsCritical_Load ≜ Critical load for the facility
Average_Power_Usage ≜ Average power usage
PUE ≜ Power usage effectiveness
PowerCost_kwh ≜ Cost per kilowatt hour
Power ≜ Monthly power costs
Other_Infrastructure ≜ Monthly cost of other infrastructure
Full_Burdened_Power ≜ Power for cooling and power for systems
Total_Cost ≜ Total cost of power

$$\text{Infrastructure} = \text{payper}\left(\frac{\text{Rate}}{12}, \text{Facility\_Amortize\_Periods} * 12, \text{Cost\_of\_Facility}, 0{,}0\right) \tag{2.12}$$

$$\text{Servers} = \text{payper}\left(\frac{\text{Rate}}{12}, \text{Server\_Amoritze\_Periods} * 12, \text{Num\_Servers} * \text{Cost\_Per\_Server}, 0{,}0\right) \tag{2.13}$$

$$\text{Power\_Cooling\_Infrastructure} = (\text{Infrastructure} * \text{Power\_Cooling\_Infrastructure\_Percentage}) \tag{2.14}$$

$$\text{Power} = \left(\text{Mega\_WattsCritical\_Load} * \frac{\text{Average\_Power\_Usage}}{1000} * \text{PUE} * \text{PowerCost\_kwh} * 24 * \frac{365}{12}\right) \tag{2.15}$$

$$\text{Other\_Infrastructure} = (\text{Infrastructure} - \text{Power\_Cooling\_Infrastructure}) \tag{2.16}$$

$$\text{Full\_Burdened\_Power} = (\text{Power\_Cooling\_Infrastructure} + \text{Power}) \tag{2.17}$$

$$\text{Total\_Cost} = (\text{Infrastructure} + \text{Servers} + \text{Power}) \tag{2.18}$$

The formulation of these equations is adapted into the MATLAB code (see Appendix 5.1).

2.3.3.4 Economic comparison of TOR vs. EOR

An important aspect of each data center cabinet is the switching equipment within the rack, of which there are two dominant approaches: Top of Rack (TOR) and End of Row (EOR). To understand the impact of choosing TOR versus EOR on life-cycle costs, an economic study was developed by [76] comparing a 144-Server configuration (see Figure 2.51 and Figure 2.53 below), as summarized in Table 2.10 below:

Table 2.10: TOR vs. EOR: Economic Comparison of Low and High Density (144 Server Cabinets) Source: [76]

CASE A		
Low-Density, 144 Server Cabinets 14 Servers Per Cabinet		
Material, Power & Maintenance	**ToR (SFP+)**	**EOR (10BASE-1)**
Material Cost	$ 11.78M	$ 8.64M
Annual Maintenance Cost	$ 1.66M	$ 1.28M
Annual Energy Cost	$ .1M	$ .04M
Total Cabling (including in Material Cost)	$ 1.22M	$ .70M
Total Cost of Ownership	$ 13.5M	$9.97M

CASE B		
High-Density, 144 Server Cabinets 40 Servers Per Cabinet		
Material, Power & Maintenance	**ToR (SFP+)**	**EOR (10BASE-1)**
Material Cost	$ 26.39M	$ 21.6M
Annual Maintenance Cost	$ 3.37M	$ 2.74M
Annual Energy Cost	$ .18M	$.11M
Total Cabling (including in Material Cost)	$ 5.12M	$ 2.08M
Total Cost of Ownership	$ 35.06M	$24.44M

The example provides a good illustration of how two different architectures can dramatically impact the density and the total costs. In the Low Density Case A, the EOR Total Cost of Ownership (TCO) was $9.97M; while in the High Density Case B, the EOR TCO increased to $24.4M. Similarly, the TOR configuration increased and remained larger than EOR in both cases. In considering the different architecture types, the problem becomes dramatically more complex and trade-offs between infrastructure design, cost, and flexibility begin to present options to the data center decision manager.

2.3.4 Summary of Data Center

In summary, we can draw the following observations about data centers:

1. The topology of data center facilities are segmented into standards-based zones.
2. The design of data centers needs to consider: Redundancy tiers levels of key infrastructure, Power Usage Effectiveness, Power cost modeling; and Economics of using Top of Rack versus End of Row networking configurations.
3. The Total Cost needs to consider both the long-term amortized facility costs and the monthly power costs. Though the initial facility cost will be amortized over 15 to 20 years, and the server/network equipment over 3 to 5 years, the incurred power cost incurred is a monthly rate, and may experience fluctuations due to changes in kilowatt per hour market rates.

In the next section, is the discussion on the approach to considering Systems Analysis.

2.4 Systems Analysis

In this work, the goal is evaluate a system, specifically, a fiber-optic system within data centers. To perform this systems-based evaluation, we need to understand: how the influences that drive 'functionality' of the architecture translate to the 'form' of the system. In the following sections is a review, and synthesis, of the corresponding literature.

2.4.1 Overview

Shown in Figure 2.43 below is the mapping of what are considered upstream influences that map to systems architecture. In this work, I consider the influences within the context of an analytical and heuristic approach, and therefore, rely mostly on the translation of the *Beneficiary/Customer Needs* to *Goals* and the optimization of the *Technology*, as highlighted in red.

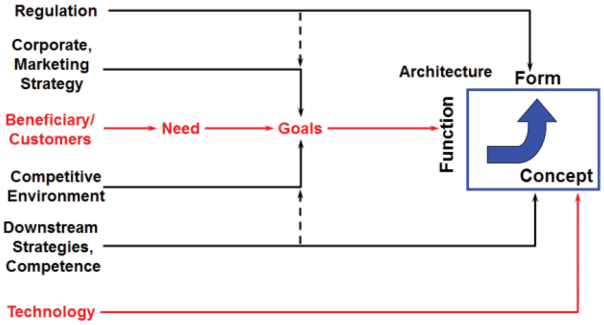


Figure 2.43: Mapping Function to Form
Source: [69]

To develop a holistic view of a system, I propose in this thesis, that we can employ a set of systems analysis tools in a sequence as shown in Figure 2.44 below as an approach to build-up the systems knowledge in a step-wise and layered manner:

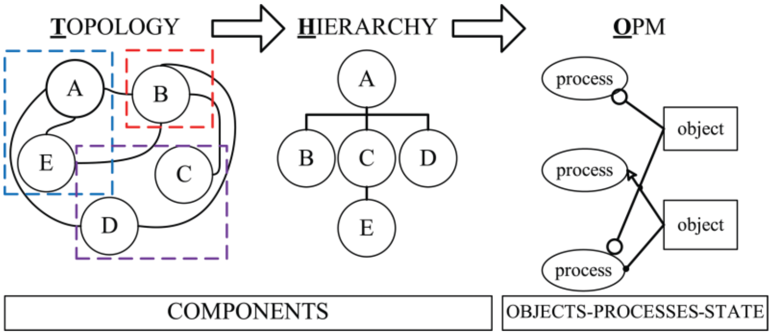


Figure 2.44: Systems Analysis Process (Topology>Hierarchy>OPM)

Shown in Figure 2.44 above, is a proposed sequence for developing an isometric systems perspective, defined in the following step-wise manner:

Step 1: Define the Topological relationships of form and function for the components. [73]

Step 2: Specify the Hierarchical relationships. [73]

Step 3: Model the Objects and processes with Object-Process Methodology (OPM). [42]

2.4.2 Topology

The three main elements of a topological representations are illustrated in Figure 2.45: (1) The components of the system, represented by {A,B,C,D,E}, (2) the connection types between the components (e.g., physical, logical, etc.), and (3) the boundary of the relationship. [69], [73]

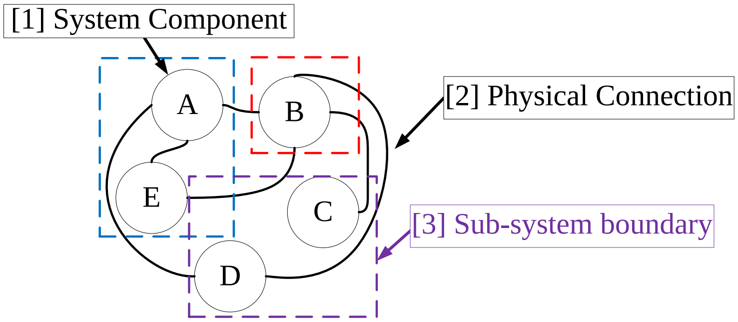


Figure 2.45: Generic Format for a Topological Representation

Utilizing the topological representations, shown in Figure 2.22 and Figure 2.40 above, is important for evaluating the physical relationships between the components. [46]

In this work, I apply the analysis towards evaluating the TIA-942 Star Topology, Figure 2.46 below, for collocation data center fiber-optic networks.

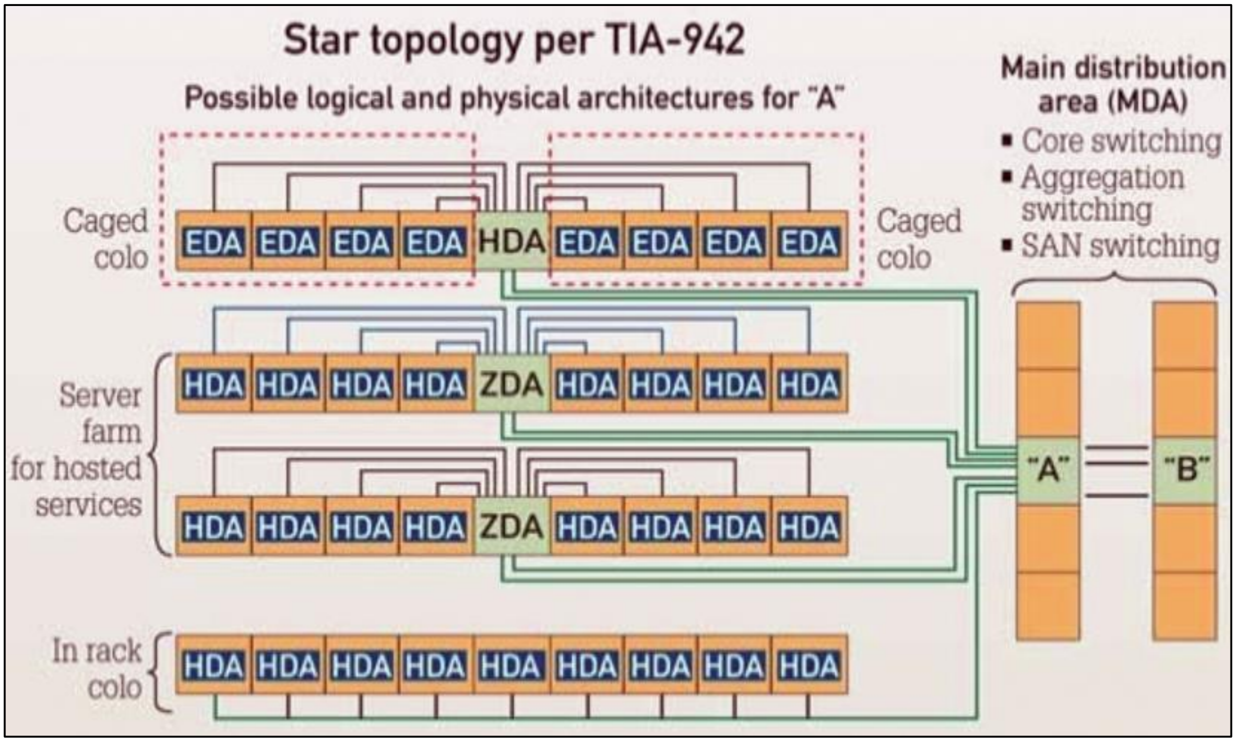


Figure 2.46: TIA-942 Star Topology
Source: [38]

2.4.3 Hierarchy

The generic format for representing a hierarchal structure, as in Figure 2.47 below, identifies the dependences for a vertically integrated system. The use of defining hierarchical relationships in the design of data centers and fiber-optic networks is essential to consider the entire system and how data will flow.

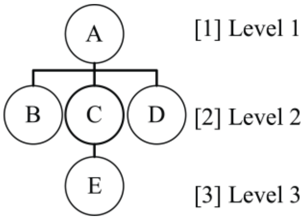


Figure 2.47: A Generalized Hierarchical Decomposition

Shown in Figure 2.48 below is an example of a hierarchical representation of one example for a data center architecture which is divided into 7 layers: Core, Aggregation, Access, Server Farms, Edge, Core, and Storage/Tape/Media Farms. The cross-connections create horizontal integration of Server Clusters.

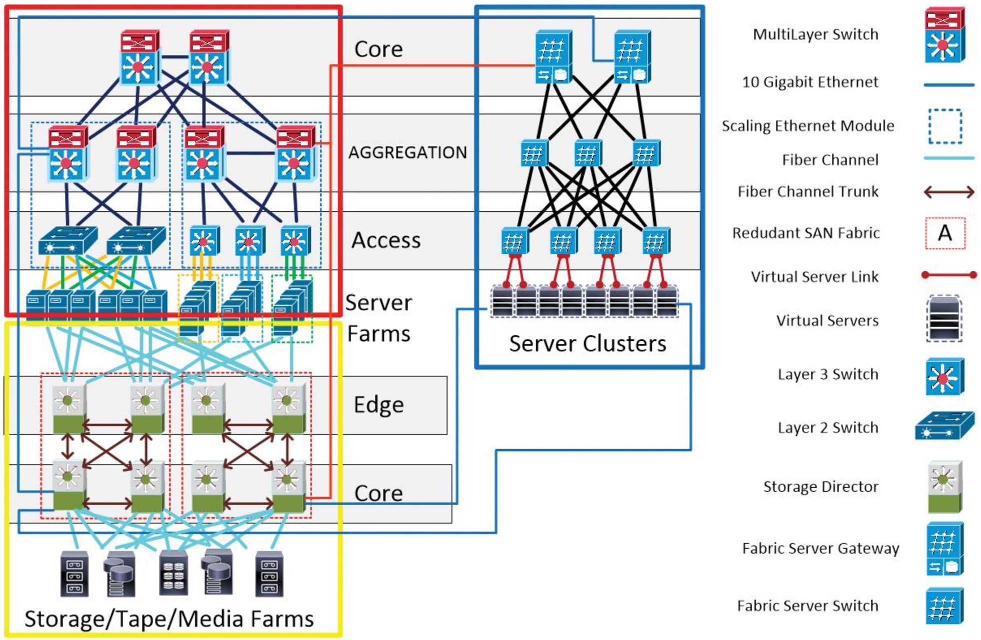


Figure 2.48: Hierarchical Architecture of a Multi-tier Data Center
Source: Adapted from Cisco Systems, Inc.

One of the most dominant hierarchical structure currently used is referred to as the FatTree [54], referring to the tree, and root structure design.

As shown in Figure 2.49 below, the floor layout of a data center is arranged in a grid configuration, with rows of rack (aka, cabinets), configured in columns, and separated by walking ailseways. In Figure 2.49 below is shown two alternatives of the configuration, and different power requirements configurations. This grid configuration is an industry format for physical configuration of the rack.

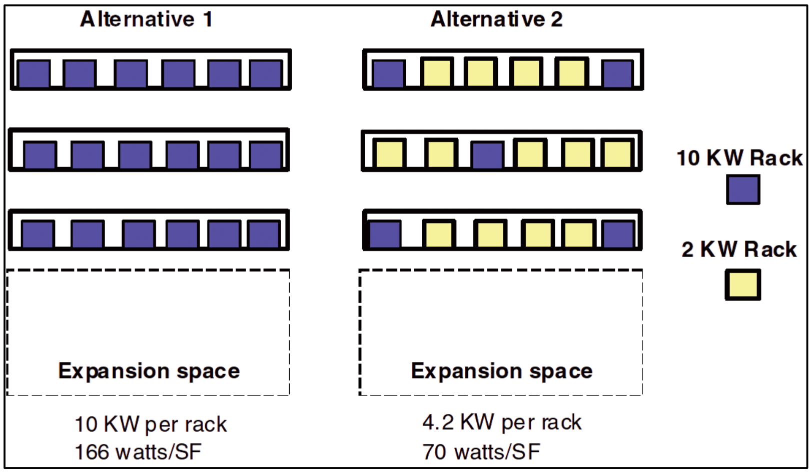


Figure 2.49: Rack Layout and Power Requirements
Source: [71]

The grid configuration for the racks is an important characteristic for the network design because it relates to the type of network hierarchical architecture that will exist in the data center to interconnect the cabinets.

2.4.3.1 Top of Rack (TOR)

The Top of the Rack (TOR) configuration shown in Figure 2.50 below utilizes one switch, typically placed at the top of the cabinet, which is connected via a fiber-optic uplink to the Aggregation Layer Switch.

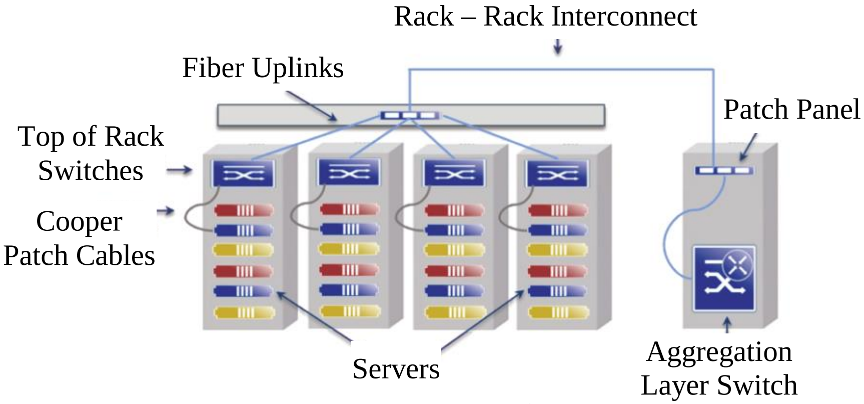


Figure 2.50: TOR Configuration
Source: [75]

In a top-down view of a data center floor plan shown in Figure 2.51 below, we can observe that the complexity and manageability quickly escalates to include cost of installation costs, maintainability, operating cost, and utilization. In the example of Figure 2.51, each row represents 14 Server Cabinets with redundant fiber (yellow and green) running from core to EOR distribution points and from there to the TOR Access Switches in each server cabinet. Point-to-Point cabling is confined to within the cabinet from TOR Switches to servers [76].

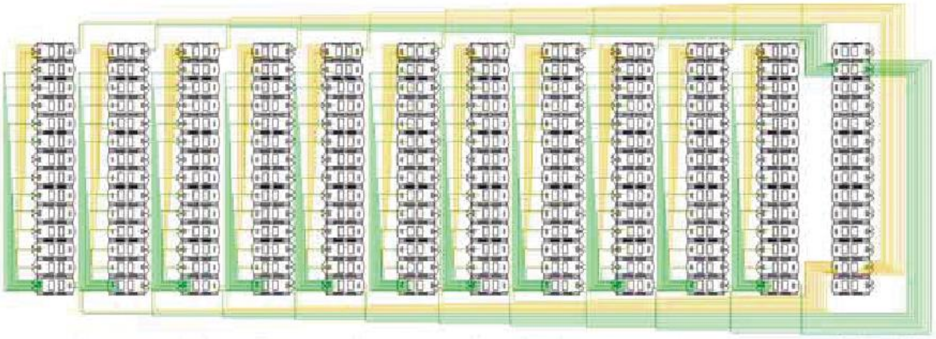


Figure 2.51: 144-Cabinet TOR Configuration in a Data Center
Source: [76]

In Table 2.11 below is summarized several of the Pros and Cons of using the TOR configuration. Notably, this hierarchy is easy to upgrade and typically known for lower cost of cabling, but higher investment in the Aggregation Layer Switch.

Table 2.11: Pros and Cons of Top of Rack (TOR)
Source: [74]

Pros	Cons
1. Per rack architecture which is easy to upgrade. 2. Problem of one switch affects lower number of servers. 3. Most of the wiring is in rack. 4. Cleaner cable management, lower costs of cables (because of length, although more is needed to aggregation level).	1. More switches to manage. 2. Worse scalability (number of STP instances, STP scalability, connections to aggregation level). 3. Increases costs of hardware, because of number of switches. 4. Single point of failure with the Aggregation Layer Switch to the entire row.

2.4.3.2 End of Rack (EOR)

The End of Row (EOR) configuration shown in Figure 2.52 below utilizes a patch panel, typically placed at the top of the cabinet, which is then interconnected to the patch panel at the End of the Row cabinet where the End of Row Switch will reside.

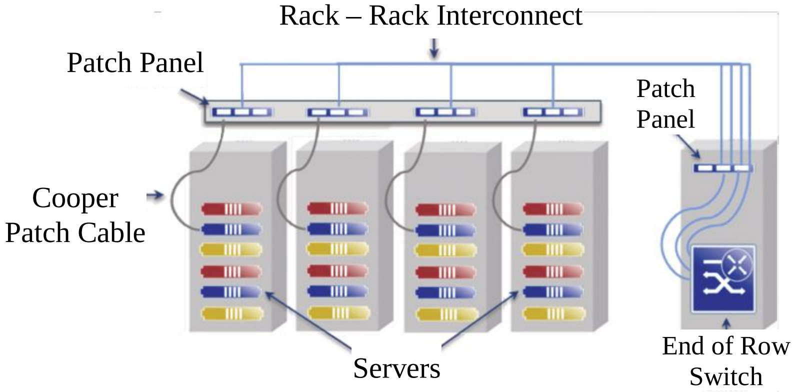


Figure 2.52: EOR Configuration
Source: [75]

In a top-down view of a data center floor plan shown in Figure 2.53 below, each row represents 14 Server Cabinets with redundant fiber (yellow and green) running from core to EOR access switches and redundant Category 6a 10GBASE-T Cooper Cabling (Red and Blue) from EOR to each Server Cabinet [76].

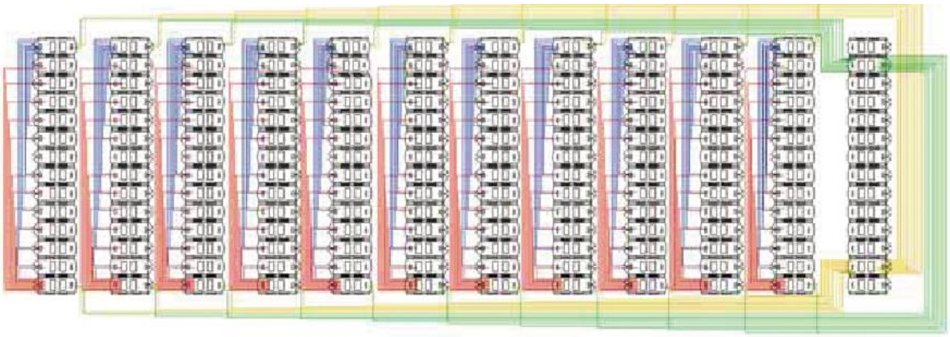


Figure 2.53: 144-Cabinet EOR Configuration in a Data Center
Source: [76]

In Table 2.12 below is presented a summary for consideration about the EOR approach to data center.

Table 2.12: Pros and Cons of End of Rack (EOR)
Source: [58]

Pros	Cons
1. Lower number of switches (less expensive hardware). 2. Better manageability of switches (lower costs to manage them). 3. Fewer ports required to distribution layer. 4. Less STP instances, better scalability on logical level. 5. Usually higher availability for servers. 6. Easy to replace module or line card (In TOR, usually whole switch must be replaced).	1. Challenges in cable management and installation, more expensive because of lengths--- much longer wiring from all the racks. 2. Worse scalability in the future, when switching to higher speeds. Worse scalability on physical level. 3. Challenges in replace or upgrade of switches – multiple racks can be affected (doesn't has to be disadvantage, if redundancy and high availability is well designed). 4. Careful planning on high availability and redundancy.

2.4.4 Object-Process Methodology (OPM) and Diagrams (OPD)

As defined by [77, p. 104], “Object-Process Methodology (OPM) is a language that describes function in a general approach that can span disciplines, and simultaneously provide precision the semantics and representations. OPM is a powerful way that captures exogenous influences, internal functions, functional attributes, subsystems, design variables, and the role of actors in the system.”

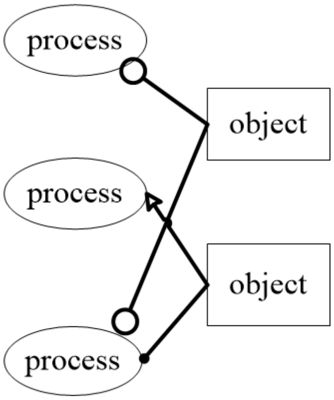


Figure 2.54: Generic Format for an OPD Representation
Reference: [42], [73], [69]

As represented in Figure 2.55 below, the OPD method is especially useful in this thesis because it helped the author to conceptualize and map the multi-layered processes (function) and objects (forms) of a complex data center system and define the boundaries of the system and scope of this thesis.

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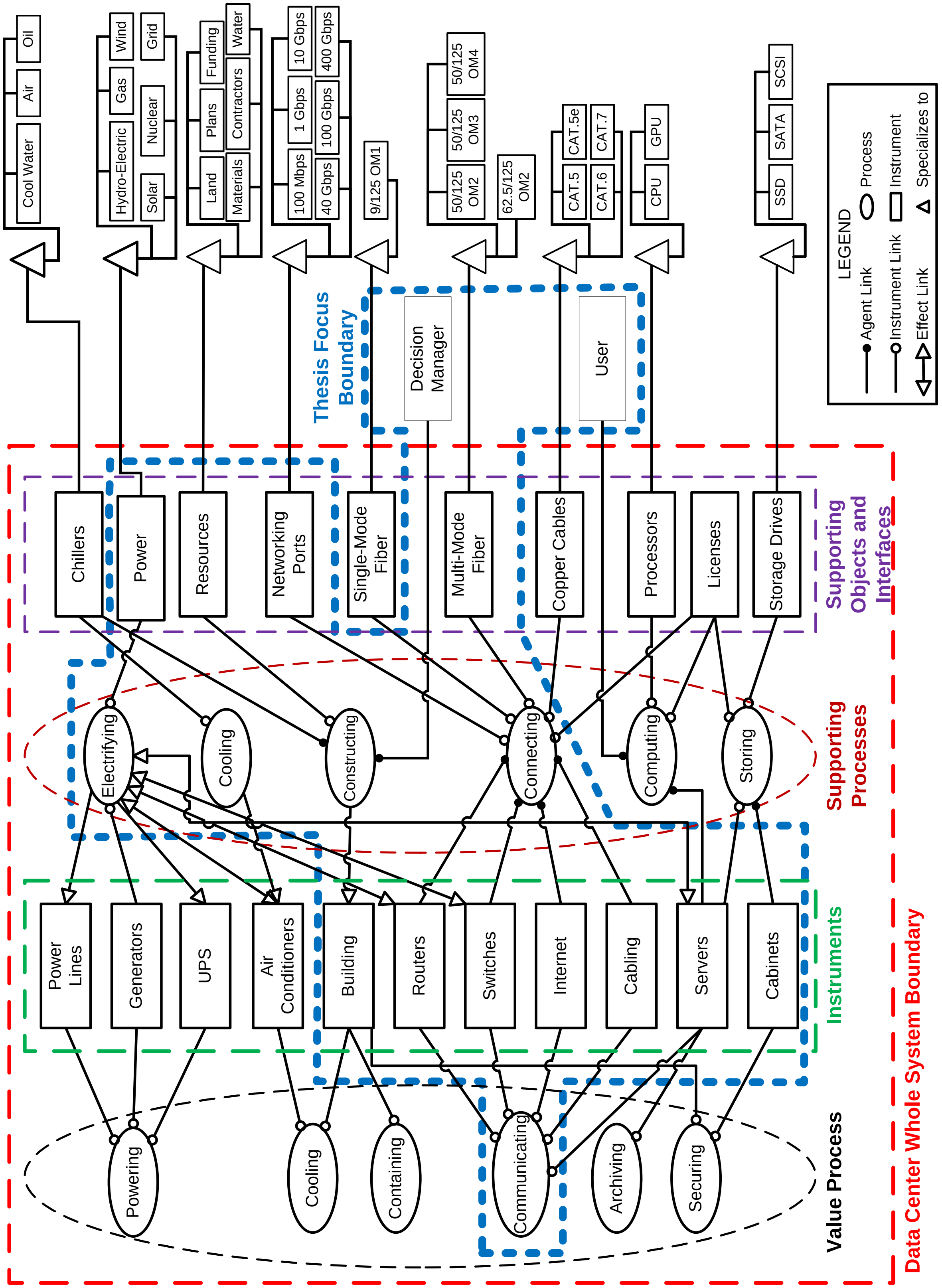


Figure 2.55: OPD of a Data Center representing Process Projected onto Form
Reference: [42], [73], [69]

From the Figure 2.55 above, the OPL specification is generated, Table 2.13 below, which helps define the multi-layered architecture of process and objects of the data center fiber-optic network system.

Table 2.13: OPL Specification for a Data Center
Reference: (Dori 2002) [42]. Generated using OPCAT II.

Generators is physical.
Building is physical.
Power Lines is physical.
Air Conditioners is physical.
Cabinets is physical.
Cabinets handles Storing.
Servers is physical.
Servers handles Computing.
Switches is physical.
Switches handles Connecting.
Cabling is physical.
Cabling handles Connecting.
Single-Mode Fiber is physical.
Multi-mode Fiber is physical.
UPS is physical.
50/125 MM OM2 is physical.
50/125 MM OM3 is physical.
50/125 MM OM4 is physical.
Storage Drives is physical.
Processors is physical.
Copper is physical.
Routers is physical.
Routers handles Connecting.
Networking Ports is physical.
Utility is physical.
Internet is physical.
Internet handles Connecting.
100 Mbps is physical.
100 Mbps is a Networking Ports.
1 Gbps is physical.
1 Gbps is a Networking Ports.
10 Gbps is physical.
10 Gbps is a Networking Ports.
40 Gbps is physical.
40 Gbps is a Networking Ports.
100 Gbps is physical.
100 Gbps is a Networking Ports.
9/125 OM1 is physical.
9/125 OM1 is a Single-Mode Fiber.
62.5/125 MM is a Multi-mode Fiber.
CAT.5 is physical.
CAT.5 is a Copper.
CAT.6A is physical.
CAT.6A is a Copper.
CAT.7 is physical.
CAT.7 is a Copper.
CAT.5e is physical.
CAT.5e is a Copper.
SSD is physical.
SSD is a Storage Drives.
SCSI is physical.
SCSI is a Storage Drives.
SATA is physical.
SATA is a Storage Drives.
CPU is physical.
CPU is a Processors.
GPU is physical.
GPU is a Processors.
NPU is physical.
NPU is a Processors.
Hydro-Electric is physical.
Hydro-Electric is an Utility.
Solar is physical.
Solar is an Utility.
Nuclear is physical.
Nuclear is an Utility.
Gas is physical.
Gas is an Utility.
Wind is physical.
Wind is an Utility.
Grid is physical.
Grid is an Utility.
Land is a Resources.
Funding is a Resources.
Licenses is a Resources.
Plans is a Resources.
Materials is a Resources.
Contractors is a Resources.
400 Gbps is a Networking Ports.
Electrifying is physical.
Electrifying requires Utility.
Electrifying affects Building, Servers, Switches, Routers, and Air Conditioners.
Electrifying yields UPS, Generators, and Power Lines.
Containing is physical.
Containing requires Building.
Communicating is physical.
Communicating requires Servers, Internet, Routers, Switches, and Cabling.
Archiving is physical.
Archiving requires Servers.
Securing is physical.
Securing requires Building and Cabinets.
Storing is physical.
Storing requires Servers and Storage Drives.
Connecting requires Networking Ports, Copper, Multi-mode Fiber, and Single-mode Fiber.
Computing is physical.
Computing requires Processors.
Powering is physical.
Powering requires Generators, Power Lines, and UPS.
Constructing is physical.
Constructing requires Utility and Resources.
Constructing yields Building.
Cooling is physical.
Cooling occurs if Building is in existent.
Cooling requires Air Conditioners.

With the OPL, we can gain an understanding of the multi-layered processes and forms of the system.

2.4.5 Summary on Systems Analysis

The implementation of the system’s thinking based approaches has enabled a methodology to deconstruct a complex system and define the interacting components. Through the SA analysis, we can develop a focus on the primary aspects of interest and study the relationship of the form and function of the system. The unified language of OPM/OPD allows us to thoroughly represent the system and the boundaries of focus. Based on the research between TOR vs EOR, the model in this work is based only on TOR configurations.

2.5 MOGA: Multi-Objective Optimization with Genetic Algorithms

In this work, I aim to consider an existing optimization approach and then develop a holistic framework that will consider the systematic definition of the design vector inputs into a model, and then empower a decision manager with an automated analysis of the trade-offs between life-cycle cost, system user capacity, and optical transmission performance (Q-factor).

In the following Sections 2.5.1 - 2.5.7 is presented a discussion on the heuristic optimization approach of Multi-objective Optimization with Genetic Algorithms (MOGA) within the Multidisciplinary System Design Optimization (MSDO) framework [4].

2.5.1 MSDO: Multi-Disciplinary System Design Optimization Framework

Shown in Figure 2.56 below is the MSDO Framework [4], which is composed of five elements: Design Vector of inputs, Simulation Model that considers inputs and outputs of the specific disciplines of the research, an Objective Vector of outputs, a coupling stage gate with various Output Evaluations methods, Optimization Algorithms, and another coupling that includes the Tradespace Exploration.

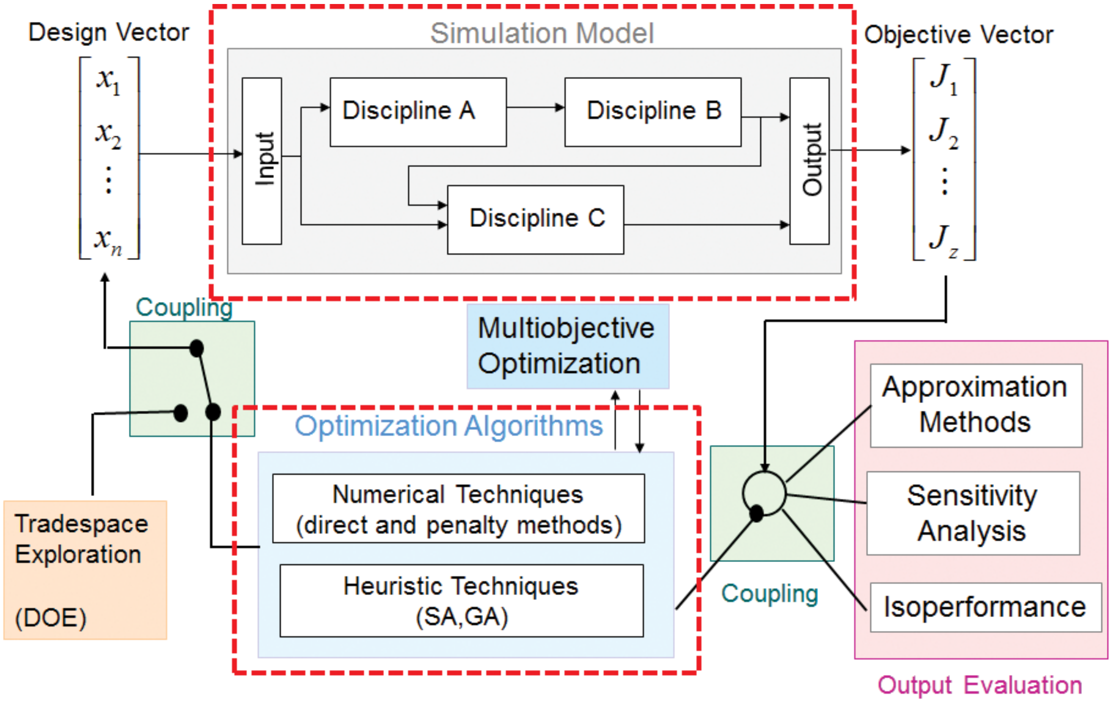


Figure 2.56: Multidisciplinary System Design Optimization Framework
Source: [4]

The two main components of the framework are the (1) Simulation Model, which evaluates for optimal designs, and the (2) Optimization Algorithms, which define the movement pattern and search approach through the design space.

To execute the process, a general process is proposed [4]:

Step 1: Define overall system requirements.
Step 2: Define design vector x, objective J and constraints.
Step 3: System decomposition into modules.
Step 4: Modeling of physics via governing equations at the module level.
Step 5: Model integration into an overall system simulation.
Step 6: Benchmarking of model with respect to a known system from past experience, if available.
Step 7: Design space exploration to find sensitive and important design variables $x_{i.}$
Step 8: Formal optimization to find min J(x).
Step 9: Post-optimality analysis to explore sensitivity and tradeoffs: sensitivity analysis, approximation methods, isoperformance, including uncertainty.

However, MSDO is a highly interactive practice, and in true practice, Steps 1 – 8 may not occur linearly, in which a branch in the process may occur. There may be an error that precipitates a solution that is unreasonable, or a feasible solution will not be found. In either case, the interaction of the research is required to make adjustments and use practical logic to adjust the research direction.

Lastly, an important aspect of this framework is to consider trade-offs for increasing difficulty. The plots shown in Figure 2.57 below represent how we should consider the level of effort for achieving high accuracy versus fidelity, and the breadth of the analysis versus the depth.

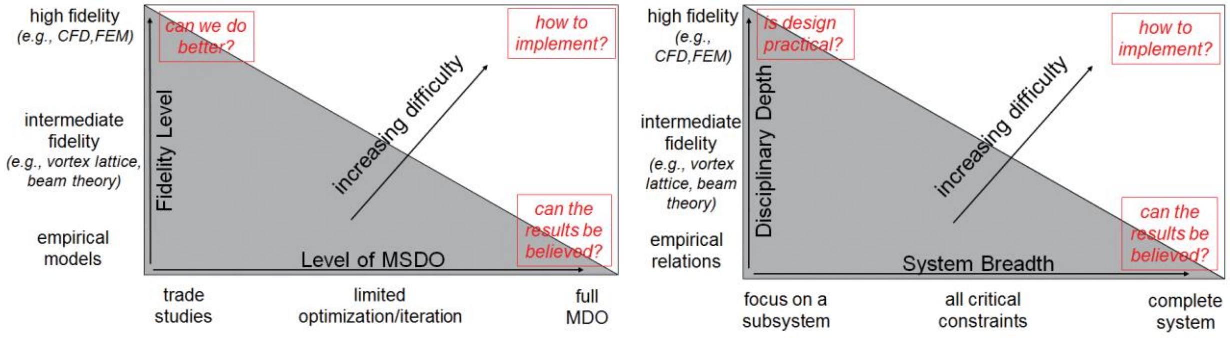


Figure 2.57: Considering Challenges of Increasing Computational Difficulty
Source:[4] (adapted from Giesing and Barthelemy 1998)

The role of the research architect is to find the proper balance for the analysis at hand.

2.5.2 Design Variables

The design space is composed of a vector **x** of n variables that forms the design space for exploration in which the values for the entries of **x** are changed in a rational manner towards a desired effect; the variables, which can have different units and types, are the controls by which the designer sets the parameters for exploring the trade-space [4].

In a fiber-optic network, a design vector can be represented as:

$$\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_i \\ \vdots \\ x_n \end{bmatrix} = \begin{bmatrix} \text{core size} \\ \text{transmit power} \\ \text{length} \\ \text{frequency} \\ \text{attentuation} \\ \text{bit rate} \\ \text{modal bandwidth} \\ \text{thermal power density} \\ \text{Rx Sensitivity} \\ \text{target Q-factor} \\ \text{cost} \end{bmatrix} \qquad \textbf{(2.19)}$$

The values for x_i can be expressed as various types [85]:

Table 2.14: Notation for Number Types

Type	Name	Example
Real	$x_i \in \mathbb{R}$	-10.1, 3.1, 5.8, 8
Integer	$x_i \in \mathbb{Z}$	-3, 0, 125
Binary	$x_i \in \{0,1\}$	11111011111
Boolean	$x_i \in \mathbb{B}$	false (0), true (1)
Complex	$x_i \in \mathbb{C}$	$4 + 8.2\sqrt{-1}$

2.5.3 Objective Functions

The process for performing a global optimization begins with the definition of the problem [6]:

$$\min_x J(x) \qquad \textbf{(2.20)}$$

subject to

$$g(x) \leq 0 \qquad \textbf{(2.21)}$$

$$h(x) = 0 \qquad \textbf{(2.22)}$$

$$x_{LB} \leq x \leq x_{UB} \qquad \textbf{(2.23)}$$

The objective function $J(x)$ is represented by Equation 2.20. In Equation 2.21 is defined the inequality constraint $g(x)$ and the equality constraint $h(x)$ by Equation 2.22. The lower bound x_{LB} and the upper-bound x_{UB} for x are defined by Equation 2.23.

Shown in Figure 2.58 below is a common example for discussing global maximum and minimum using the multivariate MATLAB “Peaks” objective function, Equation 2.24, [88]:

```
z =  3*(1-x).^2.*exp(-(x.^2) - (y+1).^2) ...
  - 10*(x/5 - x.^3 - y.^5).*exp(-x.^2-y.^2) ...
  - 1/3*exp(-(x+1).^2 - y.^2)
```

(**2.24**)

The global minimum is discovered by minimizing *z*, and the global maximum can be discovered by minimizing (-1).*z. The solution is:

$$\begin{array}{l} \text{Global Min} = [\text{X1} \quad \text{X2} \quad \text{Z}] = [0.2328 \quad -1.6135 \quad -6.5490] \\ \text{Global Max} = [\text{X1} \quad \text{X2} \quad \text{Z}] = [-0.0127 \quad 1.5827 \quad 8.1061] \end{array} \tag{2.25}$$

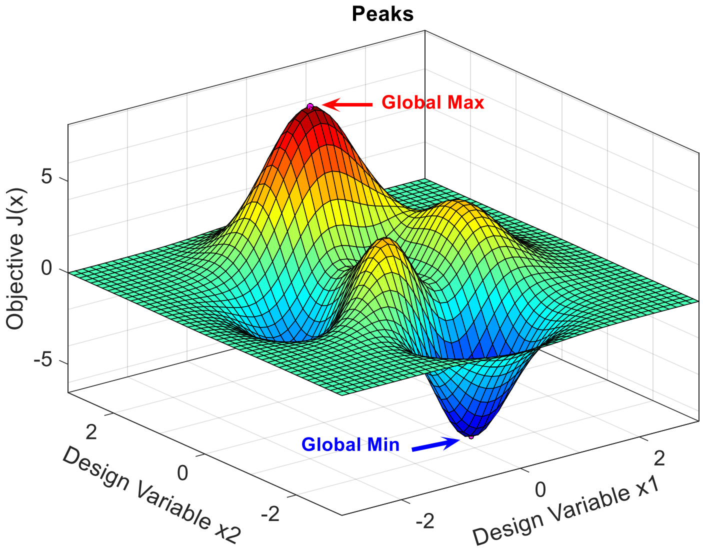


Figure 2.58: Global Max and Global Min of the Peaks Objective Function

While the Peaks example is a simple one, and can be solved fairly quickly (i.e., seconds) with modern day software, the complexity of more sophisticated problems becomes computationally too expensive, especially when solving for multiple objective functions simultaneously. Therein lies the need for developing efficient algorithms that can facilitate the discovery of the trade-space characteristics.

2.5.4 Multi-Objective Optimization

As proposed in Section 1.1 Figure 1.1 above: in managing real systems we must frequently consider multiple business objectives. The objective is a vector **J** of z system responses which we aim to maximize, or minimize, and defined as [4]:

$$\mathbf{J} = \begin{bmatrix} J_1 \\ J_2 \\ J_\mathrm{i} \\ \vdots \\ J_Z \end{bmatrix} = \begin{bmatrix} \text{cost (\$)} \\ \text{noise (dB)} \\ \text{capacity (users)} \\ \vdots \\ \text{power (W)} \end{bmatrix} \tag{2.26}$$

In Equation 2.26 is presented an example vector **J** of system-level metrics that are used when considering fiber-optics network design.

The problem formulation is then updated to reflect the multi-objective approach, with vector notation:

$$\min_{\mathbf{x}} \mathbf{J}(\mathbf{x}) \tag{2.27}$$

subject to

$$\mathbf{g}(\mathbf{x}) \leq 0 \tag{2.28}$$

$$\mathbf{h}(\mathbf{x}) = 0 \tag{2.29}$$

$$\begin{gathered} x_{i,LB} \leq x_i \leq x_{i,UB} \\ i = 1, \dots, n \end{gathered} \tag{2.30}$$

$$\mathbf{J} = [J_1(\mathbf{x}) \quad \cdots \quad J_z(\mathbf{x})]^{\boldsymbol{T}} \tag{2.31}$$

$$\mathbf{x} = [x_1 \quad \cdots \quad x_i \quad \cdots \quad x_n]^{\boldsymbol{T}} \tag{2.32}$$

$$\mathbf{g} = [g_1(\mathbf{x}) \quad \cdots \quad g_{m_1}(\mathbf{x})]^{\boldsymbol{T}} \tag{2.33}$$

$$\mathbf{h} = [h_1(\mathbf{x}) \quad \cdots \quad h_{m_2}(\mathbf{x})]^{\boldsymbol{T}} \tag{2.34}$$

The Equations 2.27 - 2.34 form the foundation for the multi-objective optimization utilized in this work.

2.5.5 Multi-Objective Heuristics with Genetic Algorithms

The motivation for heuristic optimization techniques is to develop a means for analytical computation to: 1) address local optima getting trapped and resulting in the global minimum not being accurately discovered and 2) allow continuous and discrete, $x_i \notin \mathbb{R}$, design variables [89]. By invoking a rules-based randomness into the techniques, heuristics allow for better discovery of the global optimums in situations which might otherwise not be found with the classical (i.e., gradient/calculus-based hill climbing) techniques.

Throughout time, scientists and engineers have looked to nature for inspiration in many aspects of product development, with a prime example in the field of Aeronautics and Aviation is the airplane— a by-product of bird wing designs. Similarly, in the field of global optimization, an evolutionary algorithm, called Genetic Algorithms (GA), was developed by [94], in which biological abstractions are applied to a new paradigm: "population-based metaheuristics optimizations." [6]

In the spirit of following Darwin's theory, [5] defined an algorithm, which utilizes the concept of survival of the fittest in natural selection by considering five parameters: 1) Variation, 2) Competition, 3) Offspring, 4) Genetics, and 5) Natural Selection [95]. The variation introduces the mutation, competition considers scarcity of resources, offspring are the result of fertile parents, genetics are the traits which are passed-on between generations, and natural selection is the process by which only those with the most effective traits survive. The premise of the GA is to represent a solution in binary format as a chromosome, and then mutate and crossover the alleles to re-evaluate towards convergence of the fittest solution.

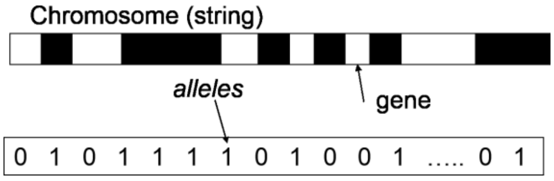


Figure 2.59: Mapping Chromosomes to Binary
Source: [89]

By adapting the principles of genetics and natural selection into optimization methods, we are able to develop computational approaches, Figure 2.60 below, that iteratively solve for optimal solutions. [96]

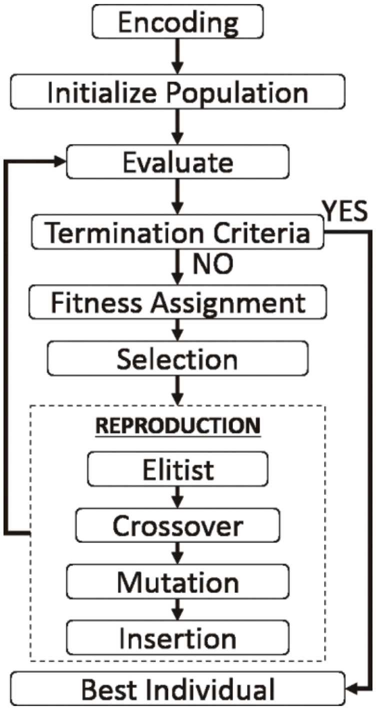


Figure 2.60: Procedure for Genetic Algorithm
Adapted from: [6], [96]

2.5.5.1 Encoding and Decoding Chromosomes

The process for encoding refers to the conversion of a string (i.e., chromosome) into binary format. In MATLAB, the 'dec2bin', 'encode', and 'decode' functions may be used. Alternatively, the MATLAB Optimization Toolbox will perform this process with the built-in procedures when used with 'gaoptimset'. Below are examples of encoding, Equation 2.35, and decoding, Equation 2.36, for the number: 2016.

ENCODING EXAMPLE: 2016 to binary

Divide by 2	Value	Remainder		Binary
1/2	0	R1	>	1
3/2	1	R1	>	1
7/2	3	R1	>	1
15/2	7	R1	>	1
31/2	15	R1	>	1
63/2	31	R1	>	1
126/2	63	R0	>	0
252/2	126	R0	>	0
504/2	252	R0	>	0
1008/2	504	R0	>	0
2016/2	1008	R0	>	0

(2.35)

2016 in binary is 11111100000

Check using MATLAB:

$\gg \mathrm{dec2bin}(2016) = 11111100000$

The decoding is the conversion from the binary number to the decimal number.

DECODING EXAMPLE: 11111100000 to decimal

Binary	1	1	1	1	1	1	0	0	0	0	0
Base2	**10**	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**0**

$$\gg \text{decode} = \mathbf{1} * 2.^{\mathbf{10}} + \mathbf{1} * 2.^{\mathbf{9}} + \mathbf{1} * 2.^{\mathbf{8}} + \mathbf{1} * 2.^{\mathbf{7}} + \mathbf{1} * 2.^{\mathbf{6}} + \mathbf{1} * 2.^{\mathbf{5}} + \mathbf{0} * 2.^{\mathbf{4}} + \mathbf{0} * 2.^{\mathbf{3}} + \mathbf{0} * 2.\hat{}\mathbf{2} + \mathbf{0} * 2.\hat{}\mathbf{1} + \mathbf{0} * 2.\hat{}\mathbf{0} \tag{2.36}$$

$$\gg \text{decode} = 2016$$

2.5.5.2 Initialize Population

The start of the algorithm requires an initial starting point, which requires the definition of the encoding parameters, size of the population, both in quantity and bits for encoding. These design decisions have a strong influence on algorithm efficiency, and therefore, careful considered is need to set these values.

2.5.5.3 Fitness

The assignment of fitness is performed on the objective value, with stronger bias towards more fitness, but ensuring diversity in the population. There are numerous methods for selecting the fitness level criteria, such a Ranking, Proportionality, Top levels, and Roulette Wheel, to name a few. With each iteration, only a select subset of parents will be selected to continue to create off-spring.

2.5.5.4 Cross-over

At a cross-over point in the chromosome, binary values of the two parents are swapped to create off-spring.

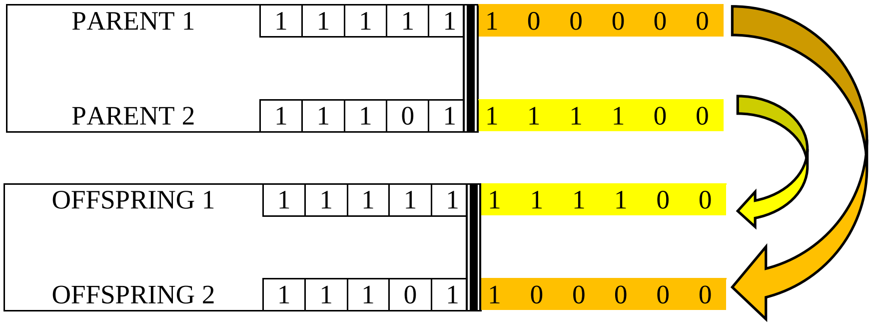


Figure 2.61: Genetic Algorithm Cross-Over

The OFFSPRING 1 contains the first half of the PARENT 1 and second half of PARENT 2. The OFFSPRING 2 contain the first half of the PARENT 2 and second half of PARENT 1. Next, based on an insertion strategy, the two OFFSPRING will then return into the algorithm and be evaluated.

2.5.5.5 Mutation

Mutation can be introduced by then flipping one of the binary values, using a random probability.

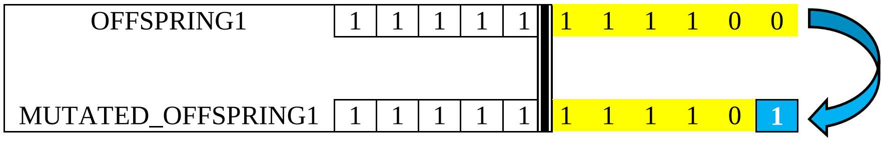


Figure 2.62: Genetic Algorithm Mutation

2.5.5.6 Elitistism and Insertion

A small percentage of the fittest individual will be guaranteed survival to the next iteration without any change in the current iteration. Other strategies for insertion include "Hall of Fame", in which past individuals are remembered and not used for the progeny.

2.5.6 Pareto Front

When considering multiple objective functions, it is useful to understand that more than one optimal solution may be achieved, which is referred to as: Pareto Optimal Solutions. To understand the trade-offs between the competing objective functions, for example, Obj1 and Obj2 in Figure 2.63 below, we generate a plot of the dominated and non-dominated solutions, and then look for the line at the edge, called a Parteo Frontier. This Pareto Front represents the optimal solutions "… for which any improvement in one objective will result in the worsening of at least one other objective." [6, p. 125]

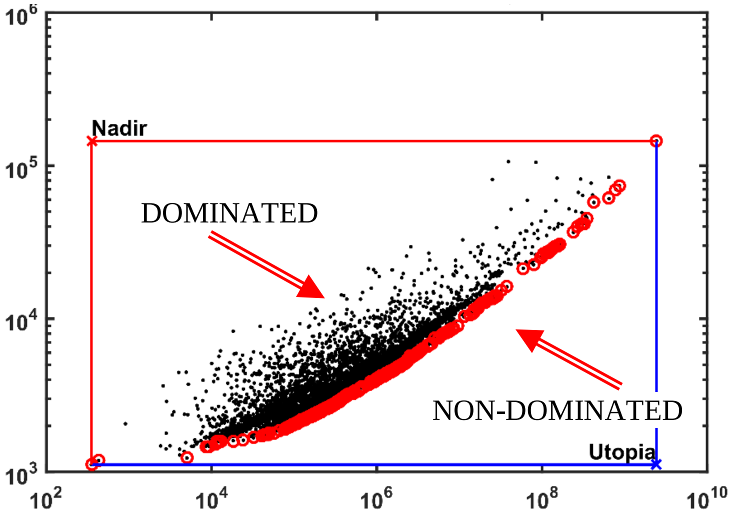


Figure 2.63: Example of a Pareto Frontier
Adapted from [4] Leo Satellite Constellation Project

With an understanding of the Pareto front, we are able to consider the trade-offs between the objective functions and select the point along the Pareto to determine the corresponding design variables that were used to yield that non-dominated solution.

2.5.7 Summary of MOGA

In summary, we draw the following observations about multi-objective optimization with genetic algorithms:

1. We can look to nature for bio-inspired approaches to optimize system designs;
2. Charles Darwin's theory of evolution and natural selection, and Gregor Mendel's discoveries of genetic inheritance have been applied to optimization theory, yielding an evolutionary algorithm to facilitate discovery of optimal solutions;
3. Encoding solutions into binary format allows for selecting cross-over, mutation, and insertion strategies for iterative evaluation;
4. Achieving more than one optimal solution leads to a tradespace evaluation of solutions;
5. In evaluating the tradespace, the solutions that are non-inferior (aka, non-dominated) will be represented along the edge of solution space, which is referred to as the Pareto frontier;
6. A Nadir is the idealized worst solution, and the Utopia is the idealized best solution; and
7. Visualizing the Pareto frontier allows a decision maker to evaluate trade-offs, and thereby improve the decision making process for evaluating system design.

In the next section, is a discussion of the approach to considering parallel computing with CPU and GPU.

2.6 Parallel Computing with CPU and GPU

The growth of computing resources as demonstrated by Moore's law [109] has brought substantial computing resources the user's desktop that once were limited to organizations with large financial resources. Enabling clusters of parallel processors has become a mainstay resource. The latest trend is shifting computational resources to harness the multi-core capabilities of Graphic Processing Units (GPU) to coincide with CPU's in parallel processing toolboxes. These parallel computing resources enable rapid computational analysis, which are implemented into the framework of this work.

2.6.1 Vectorized of Functions on the CPU

To improve the performance of the computations within MATLAB, it is best to develop the code to use arrays or matrices because MATLAB was engineered to perform optimally when using matrix-based (i.e., linear algebra) calculations. To help the researcher develop the optimal code towards functions that 'vectorize' the data, MATLAB provides built-in methods that offer sophisticated approaches to perform the vectorization of a function, which include 'meshgrids' and 'bsxfun'. To understand the benefit of coding one 'vectorize' format method over the other, a benchmarking experiment was setup to compare the *cputime* for execution of a vectorization, using three approaches: FORLOOP, MESHGRIDS, and BSXFUN.

2.6.2 Analysis of Vectorization on Computation Time with CPU

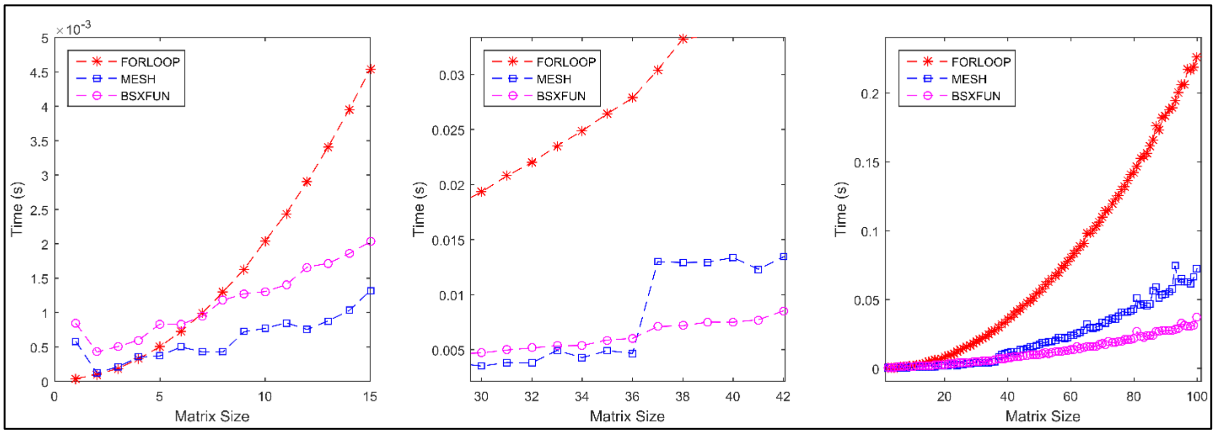


Figure 2.64: Impact of Three Vectorization Approaches on CPU Computation Time

From Figure 2.64 above, we can draw an observation that for small matrix sizes (<5), the approaches are relatively equal in time performance. For the range between ~4 to ~35, the 'for loop' should be avoided, and the 'mesh' performs best. For the matrix sizes greater than ~36, the 'bsxfun' provided the best response. Understanding the scope of the matrix size for the associated MATLAB code will help the researcher balance between the exertion of developing sophisticated coding and the performance gain. For small matrices and quick prototyping the 'for loop' is adequate; mid-size matrices, 'mesh' works well; and for the large matrices, the 'bsxfun' is best.

To increase the speed of a Genetic Algorithm optimization, the fitness function needs to be programmed in a '*vectorize'* format [105]. There are several methods to *vectorize* a function, provided by the following adopted example [104]:

$$f(x_1, x_2) = x_1^2 - 2x_1\ x_2\ + 6x_1\ + x_2\ - 6x_1 \tag{2.37}$$

Step 1: Vectorized Format of Function:

$$z = x(:,1).\wedge 2 - \ 2 * x(:,1).* x(:,2) + 6 * x(:,1) + \ x(:,2).\wedge 2\ - \ 6 * x(:,2) \tag{2.38}$$

The colon in the first entry of x indicates all the rows of x, so that $x(:,1)$ is a vector. The `.^` and `.*` operators perform elementwise operations on the vectors.

Step 2: Set the gaoptimset options 'Vectorize' to on:

```
options = gaoptimset(options,'Vectorize','on');
```

To understand the computational benefit of the *Vectorized* fitness on the GA, a benchmark comparison of a genetic algorithm [91] is performed, with a starting point of the MATLAB provided demo file: *gaoptionsdemo.m* [92]. Two versions of the file were branched and the output of the GA solver were compared.

Step 0) Modify three options to saturate the computer system

```
opts = gaoptimset(opts,'PopulationSize',100);
Population = rand(10,2);
opts = gaoptimset(opts,'Generations',500,'StallGenLimit', 100);
```

Step 1A) gaoptionsdemo_Vectorize_OFF.m

```
%% File with the Vectorize OFF by commenting off the option
%opts=gaoptimset('Vectorize','on');
```

Step 1B) gaoptionsdemo_Vectorize_ON.m

```
%% Vectorize is enabled ON
Opts = gaoptimset('Vectorize','on');
```

Presented in Table 2.15 below is shown the results of the two simulations. We observe that the 'Vectorize' option reduces the number of generations and evaluations, while yielding a better result of the objective function, all within a faster speed. For a single objective function, the performance benefit of enabling the 'Vectorize' option provides substantial benefit to the computation.

Table 2.15: Performance of a Vectorized GA for an Objective Function using *gaoptionsdemo*

	Vectorize OFF	Vectorize ON	Improvement
Number of generations:	500	138	72%
Number of evaluations:	50100	13900	72%
Best function found:	-186.731	-186.665	0%
Elapsed time (seconds):	20.064052	7.046333	65%

The number of generation and evaluations is reduced by 72% and the elapsed time by 65%, while attaining the value Best function value for the `'Vectorize','on'`.

One limitation to working with GPU's is that data must be sent and gathered after processing. The time required for this back and forth overhead transfer must be considered when evaluating the use of a GPU. To minimize the overhead transfer time, it is recommended that arrays be created directly on the GPU.

2.6.3 Analysis of Vectorized on Computation Time with GPU

In Figure 2.65 below is shown a comparison between the 'send' and 'gather' transfer speed for various arrays sizes to an nVidia GTX970 GPU.

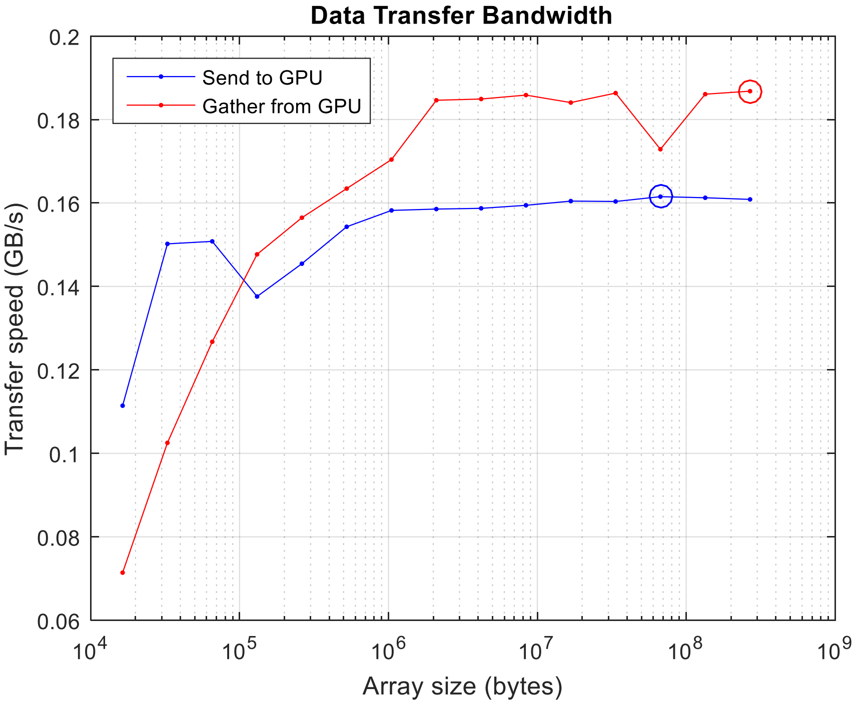


Figure 2.65: GPU Data Transfer Bandwidth (nVidia GTX970)

For arrays sizes less than 10^5 bytes, the 'sending' transfer time is greater than the gathering transfer time, and from greater than 10^5 bytes the 'gathering' time is most. From this analysis, we understand that GPU's can be useful to reduce overall computational time, but require overhead time to transfer (i.e., sending and gathering) that needs to be considered in the design of the simulations. This leads to the need of understanding when to use a GPU versus a CPU, and is discussed in the next section.

2.6.4 CPU versus GPU performance

To compare the performance of CPU and GPU, a benchmarking experiment [108] was performed with four different GPU-enabled computing instances using the Amazon EC2 GPU infrastructure:

Table 2.16: Amazon EC2 Instances GPU versus CPU

Source	Name	GPU					CPU			
		Type	Qty	Total Cores	R/W GB/S	CALC GB/S	Type	Cores	R/W GB/S	CALC GB/S
Amazon EC2	cg1.4xlarge	M2050	2	3072	328.24	327.2	E5-2670	16	14.14	76.2
Amazon EC2	g2.2xlarge	GRID K520	1	1536	116.7	93.5	E5-2670	8	16.61	76.1
Amazon EC2	g2.8xlarge	GRID K520	4	6144	471.54	374.8	E5-2670	32	17.23	134.1
Personal	workstation	GTX 970	1	1664	137.35	115.7	x5365	8	6.89	31.6

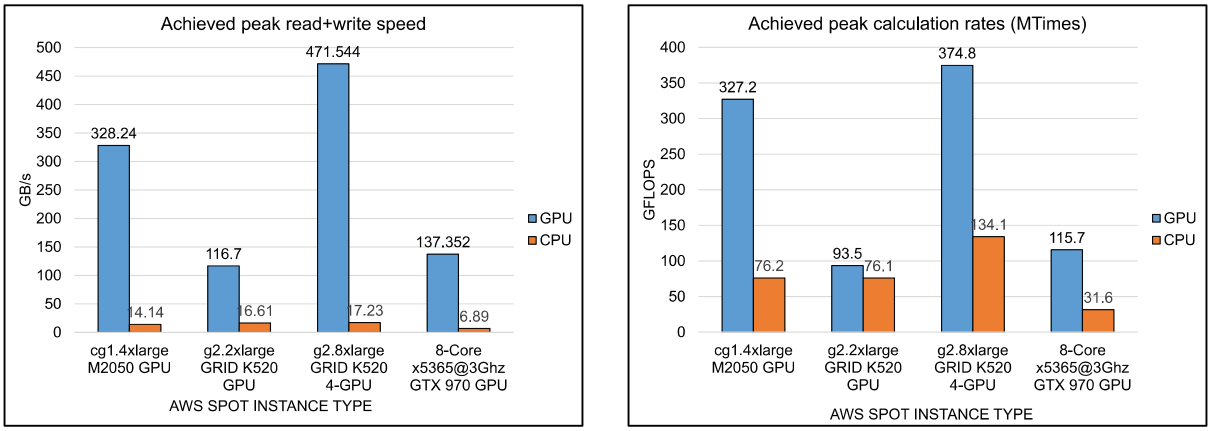


Figure 2.66: Achieved Peak Read+Write and Calculation Rates with GPU versus CPU

The results of the comparative analysis, shown in Figure 2.66 above, indicates that in all cases, the GPU outperforms the CPU. Additionally, we observe that the consumer grade GTX 970 performs well in the achieve peak read+write speeds for the GPU, which would be sufficient for low-cost desktop level processing. However, the K520 4-GPU outperforms all the other GPU because of the quad GPU and superior capability to handle double-precision computations.

2.6.5 Double vs. Single Precision

Another important aspect when considering the GPU computing is the ability to perform computations with double (greater than 10^34 decimals) and single precision (less than 10^34 decimals). Every simulation requires consideration for the precision of the computation and the corresponding values that are generated. Presented in Figure 2.67 below are the results of an analysis performed in MATLAB of the four instances comparing ‘Double’ and ‘Single’ precision for MTimes, Backslash and FFT computations.

Table 2.17: GPU: Data-Type Precision GigaFLOPS

Source	**Name**	Type	Qty	Total Cores	**DOUBLE**			**SINGLE**		
					MTimes	Backslash	FFT	MTimes	Backslash	FFT
Amazon EC2	cg1.4xlarge	M2050	2	3072	373.68	288.8	179.64	3017.89	831.15	334.22
Amazon EC2	g2.2xlarge	GRID K520	1	1536	93.34	65.37	44.82	4839.4	2000.28	772.88
Amazon EC2	g2.8xlarge	GRID K520	4	6144	328.32	265.81	67.31	1210.07	438.12	190.26
Personal	workstation	GTX 970	1	1664	117.97	16.87	60.16	3779.1	.02	.1

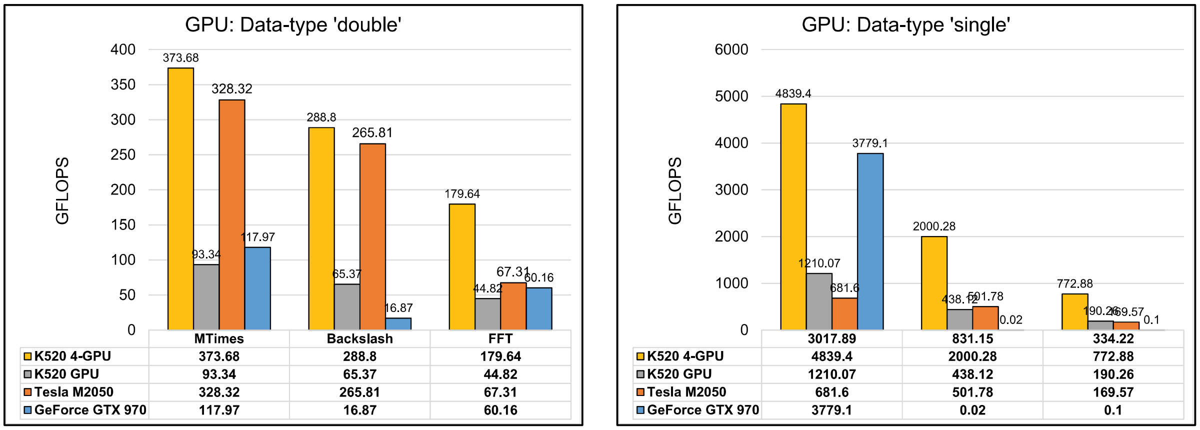


Figure 2.67: Double vs. Single Precision with GPU Computing

From the results in Figure 2.67 above, the K520 4-GPU performs the best with the largest Floating Point Operations Per Section (FLOPS), due to the four K520 GPU. The GTX970, a consumer grade GPU, performs almost as well as the K520 quad GPU for the Single Precision MTimes.

2.6.6 Summary of Parallel Computing with CPU and GPU

We draw several conclusions for this study on CPU versus GPU computing:

1) Implementing ‘Vectorize’ methods on a GPU provides performance improvement over CPU;
2) GPU computing environment provides substantial computational resources but does have an overhead in the ‘send’ and ‘gather’ transfer cputime;
3) The consumer grade GPU cards, such as the GTX 970 or Quadro business class series, can provide useful prototyping resources on a local workstations for certain computations; and
4) The Amazon EC2 g2.8xlarge instance provides a robust quad GPU configuration;
5) Researchers should consider the numerical experiments to make the proper decision for selecting the proper GPU that fits the computational size of the matrices at the lowest cost.

Drawing on these conclusions, it is a goal of this work to implement this analysis in a computational ecosystem that is enabled with the nVIDIA Cuda GPU, multi-core CPU’s, and MATLAB with the Optimization and Parallel computing toolboxes.

2.7 An Integrated Framework for Fiber-Optic Network Design

2.7.1 Framework Architecture

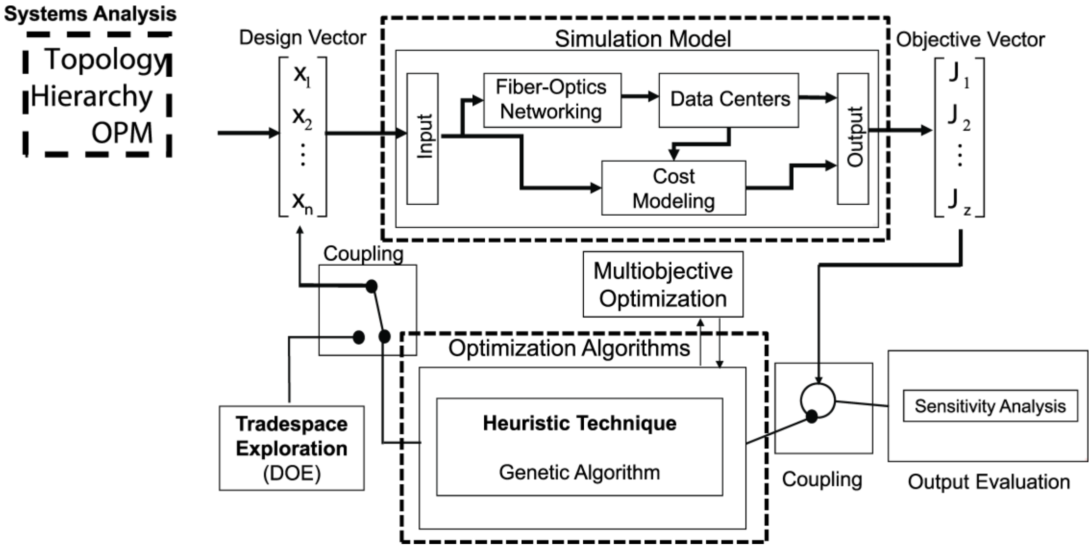


Figure 2.68: MSDO Framework Applied to Fiber-Optic Network Design
Source: Adapted from [4]

The integrated MSDO framework in this work, Figure 2.68 above, utilizes the inputs from a System Analysis (Section 2.4 above), consisting of the topology, hierarchy and OPM studies, to develop the relevant design vector input. The simulation model contains three disciplines, Fiber-Optic Networking Technology (Section 2.2 above), Data Centers Design and Financial Modeling (Section 2.3 above), each with a set of relevant equations and constraints. The output of the simulation is an objective vector, which is evaluated using a sensitivity analysis and coupled to an optimization using multi-objective genetic heuristic algorithm (Section 2.5.5 above). Lastly, an exploration is performed to discover the non-dominated Pareto frontier (2.5.6 above) and plotted.

2.7.2 Flow of Integrated Framework Simulation Operation

Shown in Figure 2.69 below is the flow of operating the framework.

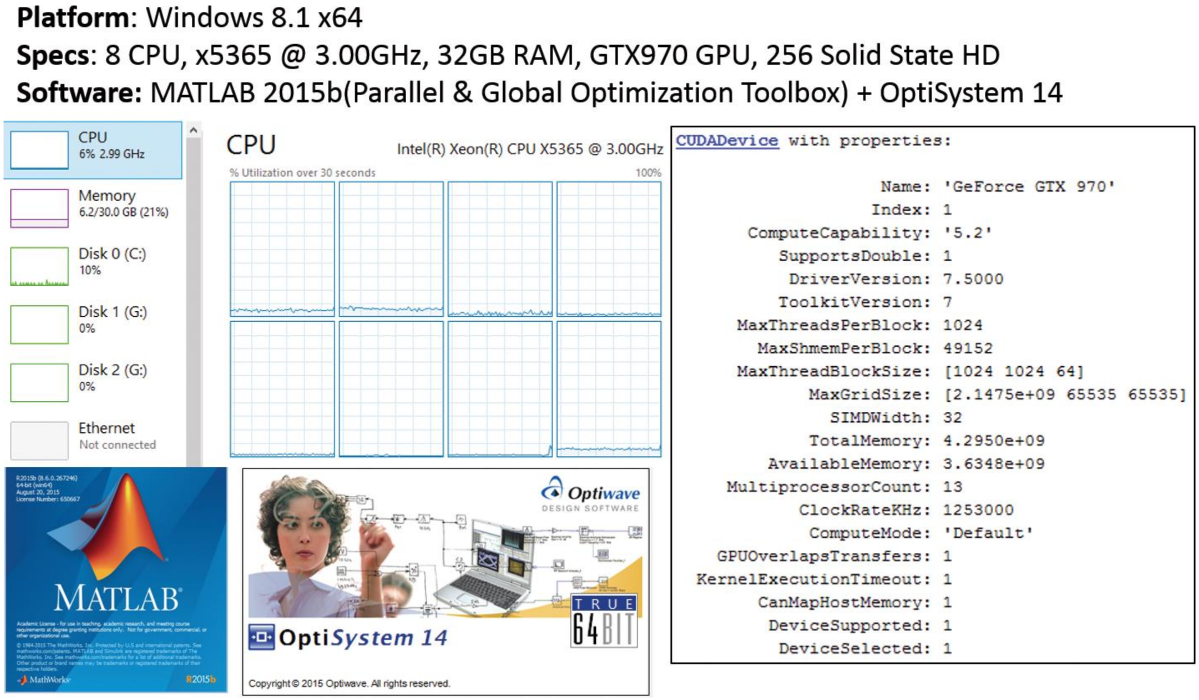
Objective	Optimization	Description	Units	Equations
J_1	Minimize	Lifecycle Cost	$	[84]
J_2	Maximize	Capacity	Users	[90], Appendix 5.1
J_3	Maximize	Optical Transmission	Q-factor	OptiSystem Analysis

⇩

MATLAB:
Genetic Algorithm Optimization, Pareto Frontier Analysis, Sensitivity Analysis

Figure 2.69: Flow of Framework Operation

2.7.3 Ecosystem and Tools for the Analysis



Platform: Windows 8.1 x64
Specs: 8 CPU, x5365 @ 3.00GHz, 32GB RAM, GTX970 GPU, 256 Solid State HD
Software: MATLAB 2015b(Parallel & Global Optimization Toolbox) + OptiSystem 14

```
CUDADevice with properties:

                      Name: 'GeForce GTX 970'
                     Index: 1
         ComputeCapability: '5.2'
            SupportsDouble: 1
             DriverVersion: 7.5000
            ToolkitVersion: 7
        MaxThreadsPerBlock: 1024
          MaxShmemPerBlock: 49152
        MaxThreadBlockSize: [1024 1024 64]
               MaxGridSize: [2.1475e+09 65535 65535]
                 SIMDWidth: 32
               TotalMemory: 4.2950e+09
           AvailableMemory: 3.6348e+09
       MultiprocessorCount: 13
              ClockRateKHz: 1253000
               ComputeMode: 'Default'
      GPUOverlapsTransfers: 1
    KernelExecutionTimeout: 1
          CanMapHostMemory: 1
           DeviceSupported: 1
            DeviceSelected: 1
```

Figure 2.70: Ecosystem and Tools for Numerical Analysis

As shown in Figure 2.70, this work utilizes four hardware technologies to perform the analysis: 8 x5365 CPU processors, 256 SSD Hard-drive, nVidia GTX970 GPU, and 32 GB EEC RAM.

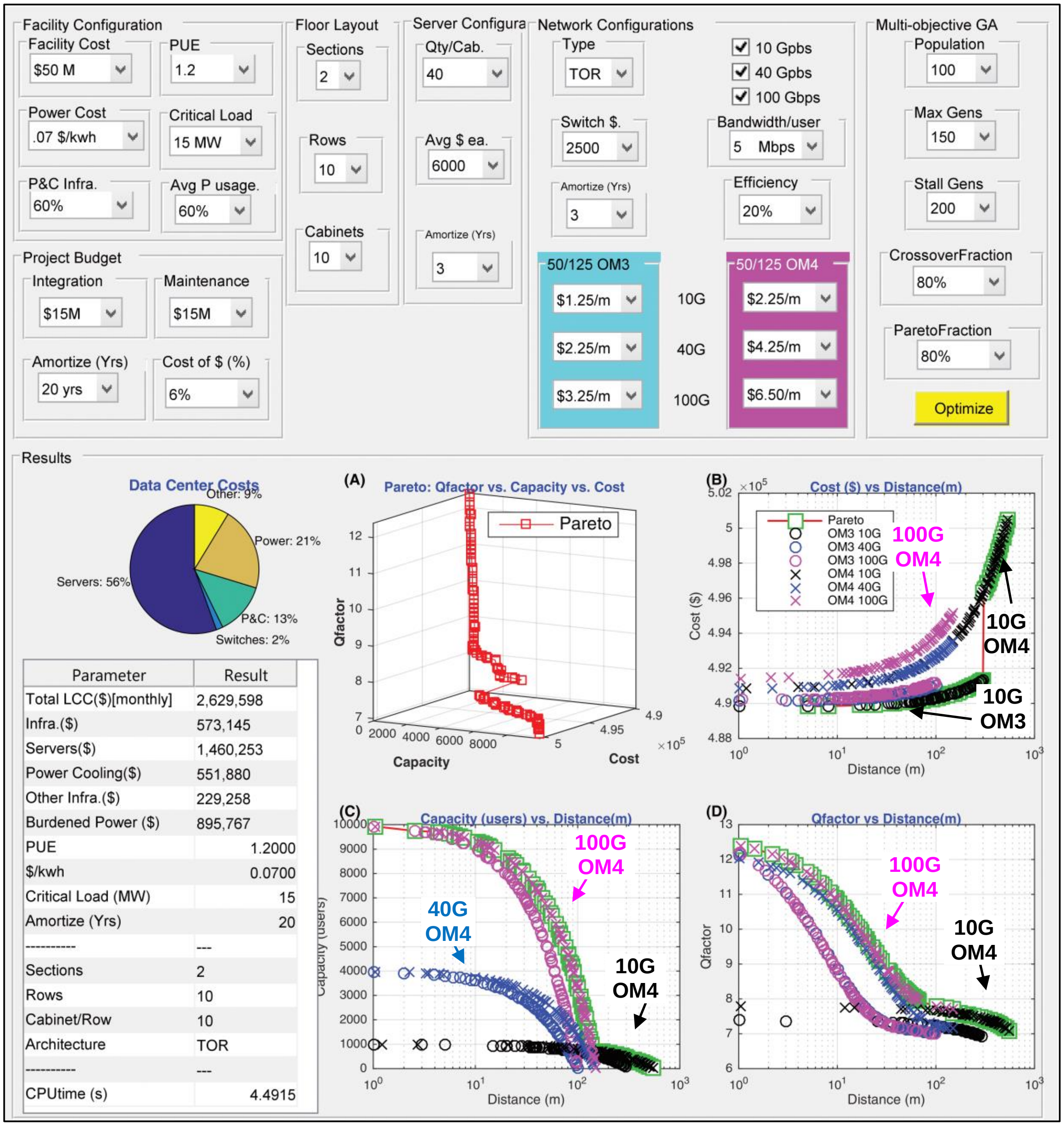
The software technologies utilized in this thesis are summarized in Table 2.18 below:

Table 2.18: Description of Software Tools for the Numerical Analysis

SOFTWARE	DESCRIPTION	ACCESS	FUNCTION
Windows 8.1 x64	Operating system	Academic License	Manage software and computation resources.
MATLAB 2015b	Matrix based computational and numerical programming	Academic License	Optimization and numerical analysis with Genetic Algorithms.
OptiSystem 14	Fiber-optic network simulation	Academic License	Study the BER and Q-Factors performance for optical networks. **[50], [51]**

2.7.4 Software Dashboard Automation

To meet one the objectives of this thesis in creating a tool for decision managers, a MATLAB-based software GUI, Figure 2.71 below, is programmed (Appendix 5.1) to facilitate the selection of parameters for a data center, multi-mode optical fiber, bandwidth, and the multi-objective genetic algorithm solver. The MATLAB code in this work utilizes a GPU, therefore a GPU with compute capability above 2.0 is required [103]. The output yields a pie chart, table of life-cycle costs, and Pareto frontiers trade-off curves for the optical network with color and shaped coded optimal solution markers.



Facility Configuration
Facility Cost: $50 M
PUE: 1.2
Power Cost: .07 $/kwh
Critical Load: 15 MW
P&C Infra.: 60%
Avg P usage.: 60%

Project Budget
Integration: $15M
Maintenance: $15M
Amortize (Yrs): 20 yrs
Cost of $ (%): 6%

Floor Layout
Sections: 2
Rows: 10
Cabinets: 10

Server Configura
Qty/Cab.: 40
Avg $ ea.: 6000
Amortize (Yrs): 3

Network Configurations
Type: TOR
Switch $.: 2500
Amortize (Yrs): 3
☑ 10 Gpbs
☑ 40 Gpbs
☑ 100 Gbps
Bandwidth/user: 5 Mbps
Efficiency: 20%

	50/125 OM3		50/125 OM4
	$1.25/m	10G	$2.25/m
	$2.25/m	40G	$4.25/m
	$3.25/m	100G	$6.50/m

Multi-objective GA
Population: 100
Max Gens: 150
Stall Gens: 200
CrossoverFraction: 80%
ParetoFraction: 80%

Results

Parameter	Result
Total LCC($)[monthly]	2,629,598
Infra.($)	573,145
Servers($)	1,460,253
Power Cooling($)	551,880
Other Infra.($)	229,258
Burdened Power ($)	895,767
PUE	1.2000
$/kwh	0.0700
Critical Load (MW)	15
Amortize (Yrs)	20
----------	---
Sections	2
Rows	10
Cabinet/Row	10
Architecture	TOR
----------	---
CPUtime (s)	4.4915

Figure 2.71: Software Dashboard
[MATLAB code provided in Appendix 5.1, GPU with compute capability 2.0 required]

In Plot A is the Pareto frontier for Q-factor versus Capacity (users) versus Cost ($), and in Plots B, C, and D, are the plots of each aspect versus distance (meters), with the corresponding Pareto optimal identified inside a red square. For Plot B we minimize Cost and in Plots C and D, we maximize the Capacity and Q-factor. To read the plots, the Pareto markers are characterized by color (**100G is magenta**, **40G is blue**, and **10G is black**), and by shape (X is OM4 and O is OM3). For example, in the Figure 2.71: Plot C, observe magenta X (100G OM4) at high capacity and shorter distance, and black X (**10G OM4**) at lower capacity and longer distance. We expect to see steep descents in the 40G and 100G solutions due to distance constraints (Table 2.3 above).

2.7.5 Summary of the Theory and Framework

In this section was synthesized the theories from the literature review into an integrated framework for data center and fiber-optic network system design, which was then programmed into a MATLAB-based GUI (Appendix 5.1). In the following section, the framework is applied with simulation and numerical analysis.

3 Simulation and Numerical Analysis

3.1 Implementation Approach

This work implements the numerical and simulation analysis in an 8-step process:

Step 1: Configure the simulation platform for a bidirectional optical network with a Star topology.

Step 2: Apply to multi-mode OM3 and OM4.

Step 3: Branch the framework to four case studies, using OM3 and OM4 multimode fiber for three network speeds: 10G, 40G, and 100G.

Nomenclature:

{#}S ≜ Quantity, {#}, of sections being evaluated
{#}R ≜ Quantity, {#}, of rows being evaluated
{#}C ≜ Quantity, {#}, of cabinets being evaluated
1S.1R.1C ≜ One section by one rows by one cabinet
1S.1R.10C ≜ One section by one row by 10 cabinets
1S.10R.10C ≜ One section by 10 rows by 10 cabinets
2S.10R.10C ≜ Two sections by 10 rows by 10 cabinets

Table 3.1: Summary of the Step-wise Approach for Case Studies

		10G		**40G**		**100G**	
Case#	**Config.**	**OM3**	**OM4**	**OM3**	**OM4**	**OM3**	**OM4**
1	**1S.1R.1C**	Step 3.1A	Step 3.1B	Step 3.1C	Step 3.1D	Step 3.1E	Step 3.1F
2	**1S.1R.10C**	Step 3.2A	Step 3.2B	Step 3.2C	Step 3.2D	Step 3.2E	Step 3.2F
3	**1S.10R.10C**	Step 3.3A	Step 3.3B	Step 3.3C	Step 3.3D	Step 3.3E	Step 3.3F
4	**2S.10R.10C**	Step 3.4A	Step 3.4B	Step 3.4C	Step 3.4D	Step 3.4E	Step 3.4F

In Figure 3.1 is a representation of Steps 4 - 7, which begins with evaluating one cabinet (1S.1R.1C) and expands to a two sections configuration of 200 total cabinets (2S.10R.10C). The case study analysis is performed on 10G, 40G, and 100G networks, using OM3 and OM4 multi-mode optical-fiber.

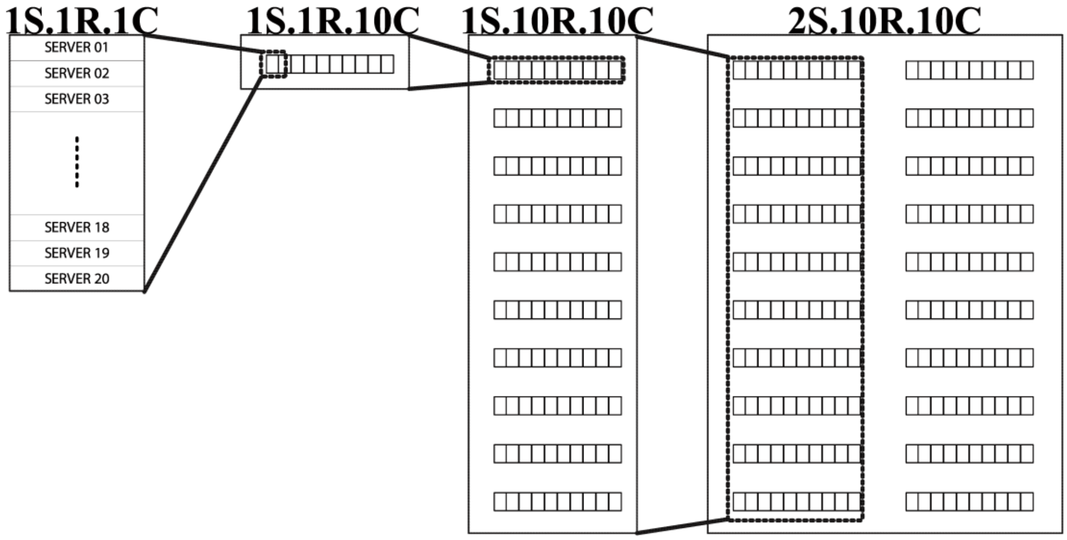


Figure 3.1: Nested Implementation Approach

Step 4: Calibrate the TX Power using the Single-Parameter-Optimization (SPO) to Q-factor = 7 ± .1 at the max distance (see Table 2.3 above) using the Optisystem simulator.

Table 3.2: Max Distance for Single-Parameter Optimization of Power to Q-factor = 7 ± .1

	10G	40G	100G
OM3	300 meters	100 meters	100 meters
OM4	550 meters	150 meters	150 meters

In this work, the total distance sweeps are linearly distributed to 25 iterations. To minimize error, distance was started at 2 meters. The SPO is performed on Iteration#25, so the maximum distance is Q=7.

Step 5: Setup the nested parameter sweeps for the length for the configuration.

- **Step 5.1:** Configure the sweep lengths to the Aggregation switch.
- **Step 5.2:** Configure the sweep lengths from the Aggregation switch to the TOR cabinet switches.
- **Step 5.3:** Configure the nested parameter sweeps.

Step 6: Perform the simulation for each case study.

Step 5: Export the results to MATLAB.

Step 6: Determine the fitted curve of the line for the Q-factor vs Length. To build the integrated framework and the life-cycle costs of optical-fiber in data centers, we need to understand the relationship between the Power (Watts) versus the length and the Q-factor versus length of the optical-fiber. By utilizing the OptiSystem simulation tool, we develop the data for the fitted equations, with the goal of minimizing the power requirements such that Q-factor = 7 +/- .1.

Step 7: With the fitted equations functions, perform the MOGA analysis to determine the optimal design of life-cycle costs, user capacity, optical transmission loss.

Step 8: Perform sensitivity analysis.

Step 9: Review and discuss the results.

3.2 Problem Formulation

Focusing on minimizing Life-cycle Cost (\$), maximizing System Capacity (users), maximizing Optical Quality (Q-factor), the problem is formulated in Equation 3.1 below:

$$\min_{x} J(\mathbf{x},\mathbf{p}) = \begin{bmatrix} J_1(\mathbf{x},\mathbf{p}) \\ J_2(\mathbf{x},\mathbf{p}) \\ J_3(\mathbf{x},\mathbf{p}) \end{bmatrix} = \begin{bmatrix} LifeCycleCost(\mathbf{x},\mathbf{p})\ [\$M] \\ -SystemCapacity(\mathbf{x},\mathbf{p})\ [users] \\ -OpticalQuality(\mathbf{x},\mathbf{p})\ [Q\text{-}factor] \end{bmatrix} \tag{3.1}$$

$$s.t.\quad \mathbf{g}(\mathbf{x},\mathbf{p}) \le 0$$
$$\mathbf{h}(\mathbf{x},\mathbf{p}) = 0$$

$$\mathbf{x} = [x_1^r \quad x_2^r \quad x_3^r \quad x_4^r \quad x_5^r \quad x_6^r \quad x_7^r \quad x_8^r \quad x_9^r \quad x_{10}^r \quad x_{11}^r]^T$$
$$r = 1,2,3,\dots 6$$

$r = 1$ is Multimode 50/125 10G OM3
$r = 2$ is Multimode 50/125 10G OM4
$r = 3$ is Multimode 50/125 40G OM3
$r = 4$ is Multimode 50/125 40G OM4
$r = 5$ is Multimode 50/125 100G OM3
$r = 6$ is Multimode 50/125 100G OM4

3.3 Definition of Design Vectors

Presented in Figure 3.2 below is a summary of the input and outputs of the model for the fiber-optic network design optimization problem. The design vector, **x**, is comprised of eleven design variables. The design vector has six parameters: 2 cable types (OM3 and OM4) at three speeds (10G, 40G, and 100G) each. The constraints are defined by $g_j(x,p)$ and $h_k(x,p)$. The upper-bound and lower-bound are defined by, UB and LB, respectively. To maximize we multiple by (-1). The output yields a vector, $J(\mathbf{x}^*)$, of optimal values.

Design Vector ⇨ **Model** ⇨ **Output**

$$\mathbf{x} = \begin{bmatrix} x_1^r \\ x_2^r \\ x_3^r \\ x_4^r \\ x_5^r \\ x_6^r \\ x_7^r \\ x_8^r \\ x_9^r \\ x_{10}^r \\ x_{11}^r \end{bmatrix} = \begin{bmatrix} \text{TX: bit rate} \\ \text{TX: transmit power} \\ \text{TX: frequency} \\ \text{CH: length} \\ \text{CH: attentuation} \\ \text{CH: core size} \\ \text{CH: modal bandwidth} \\ \text{CH: cost} \\ \text{RX: thermal density} \\ \text{RX: sensitivity} \\ \text{RX: target Q-Factor} \end{bmatrix}$$
$$r = 1,2,3,4,5,6$$

$$\min_{x} \mathbf{J}(\mathbf{x},\mathbf{p}) = \begin{bmatrix} J_1 \\ J_2 \\ J_3 \end{bmatrix} = \begin{bmatrix} \text{cost} \\ \text{(-1)*capacity} \\ \text{(-1)*Q-factor} \end{bmatrix}$$

$$g_j(x,p) \le 0 \quad j = 1,2,\dots m_1$$
$$h_k(x,p) = 0 \quad k = 1,2,\dots m_2$$
$$x_{i,LB} \le x_i \le x_{i,UB} \quad i = 1,2,\dots n$$

$$\mathbf{J}(\mathbf{x}^*) = \begin{bmatrix} \text{life-cycle cost[\$]} \\ \text{capacity[users]} \\ \text{optical quality[Q-factor]} \end{bmatrix}$$

Figure 3.2: Input and Output of the Model

In the design vector: “TX:” refers to Transmitter, “CH:” refers to Channel, and “RX:” refers to Receiver.

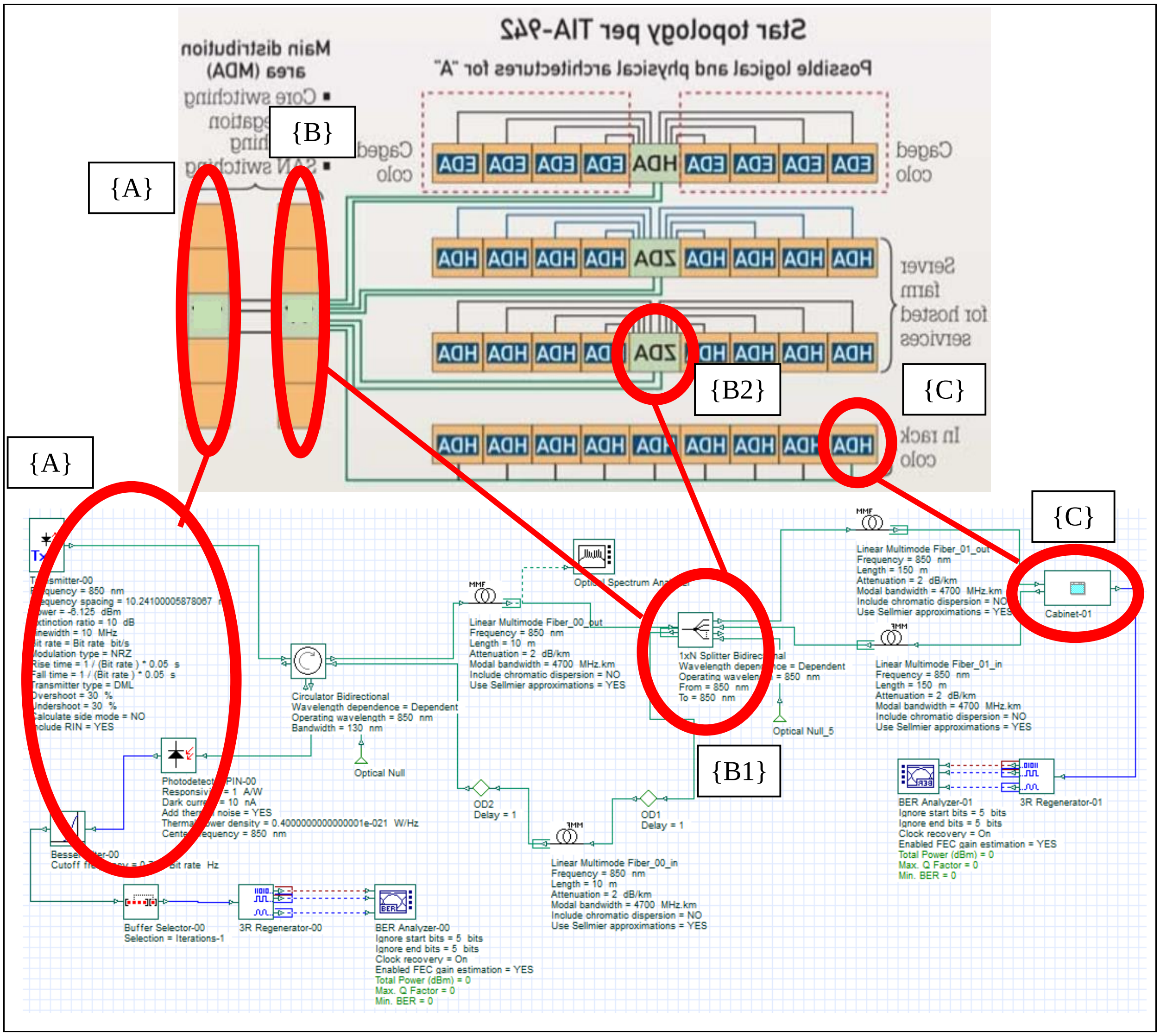
3.4 Generalized OptiSystem Simulation Framework for Star Topology

The control diagram for a bi-directional multi-mode optical network, Figure 3.3 below, is developed with OptiSystem to emulate the TIA-942 Star Topology (refer to Section 2.4.2, Figure 2.46 above):

{A} is optical transmitter

{B1} & {B2} are bidirectional splitters to emulate a aggregation switch

{C} is a cabinet with a Top of Rack (TOR) switch



T   smitter-00
F quency = 850 nm
  equency spacing = 10.24100005878067
  wer = -8.125 dBm
  xtinction ratio = 10 dB
  inewidth = 10 MHz
  it rate = Bit rate bit/s
  Modulation type = NRZ
Rise time = 1 / (Bit rate) * 0.05 s
Fall time = 1 / (Bit rate) * 0.05 s
Transmitter type = DML
  vershoot = 30 %
  ndershoot = 30 %
  alculate side mode = NO
  nclude RIN = YES

Circulator Bidirectional
Wavelength dependence = Dependent
Operating wavelength = 850 nm
Bandwidth = 130 nm

Photodetect   PIN-00
Responsivi   = 1 A/W
Dark curr   = 10 nA
Add ther   noise = YES
Therma   wer density = 0.4000000000000001e-021 W/Hz
Cente   equency = 850 nm

Besse   ter-00
Cutoff fr   = 0.   Bit rate Hz

Buffer Selector-00
Selection = Iterations-1

3R Regenerator-00

BER Analyzer-00
Ignore start bits = 5 bits
Ignore end bits = 5 bits
Clock recovery = On
Enabled FEC gain estimation = YES
Total Power (dBm) = 0
Max. Q Factor = 0
Min. BER = 0

Linear Multimode Fiber_00_out
Frequency = 850 nm
Length = 10 m
Attenuation = 2 dB/km
Modal bandwidth = 4700 MHz.km
Include chromatic dispersion = NO
Use Sellmier approximations = YES

1xN Splitter Bidirec   nal
Wavelength depen   nce = Dependent
Operating wavelen   = 850 nm
From = 850 nm
To = 850 nm

OD2
Delay = 1

OD1
Delay = 1

Linear Multimode Fiber_00_in
Frequency = 850 nm
Length = 10 m
Attenuation = 2 dB/km
Modal bandwidth = 4700 MHz.km
Include chromatic dispersion = NO
Use Sellmier approximations = YES

Linear Multimode Fiber_01_out
Frequency = 850 nm
Length = 150 m
Attenuation = 2 dB/km
Modal bandwidth = 4700 MHz.km
Include chromatic dispersion = NO
Use Sellmier approximations = YES

Cabinet-01

Linear Multimode Fiber_01_in
Frequency = 850 nm
Length = 150 m
Attenuation = 2 dB/km
Modal bandwidth = 4700 MHz.km
Include chromatic dispersion = NO
Use Sellmier approximations = YES

BER Analyzer-01
Ignore start bits = 5 bits
Ignore end bits = 5 bits
Clock recovery = On
Enabled FEC gain estimation = YES
Total Power (dBm) = 0
Max. Q Factor = 0
Min. BER = 0

3R Regenerator-01

Figure 3.3: Bi-Directional Multi-Mode Fiber Optic Star Topology Network [note: Star TIA-942 image is purposely flipped to more easily align with the Optisystem layout]

With the proposed framework, the nested distanced lengths of multi-mode fiber are sweeped, and additional {B's} may be added to emulate {D} in the TIA topology.

3.5 Case Study Simulation Parameters

In Table 3.3 below are the configurations settings utilized in the MSDO- GUI for the four theoretical case studies. The input parameters are based on assumed values of the potential size of the corresponding data center and the network, as garnered from the interviews, data center tours, literature review, and [3].

Table 3.3: Case Study Parameters

		Case 1 1S.1R.1C	Case 2 1S.1R.10C	Case 3 1S.10R.10C	Case 4 2S.10R.10C
Facility Configuration	Facility Costs:	$5 M	$10M	$20M	$40M
	PUE:	1.6	1.6	1.4	1.2
	Power Cost:	.08 $/kwh	.08 $/kwh	.07 $/kwh	.07 $/kwh
	Critical Load:	5 MW	5 MW	10 MW	10 MW
	P&C Infrastructure:	60%	60%	60%	82%
	Average Power Usage:	60%	60%	60%	80%
Project Budget	Integration:	$5 M	$5 M	$10 M	$15 M
	Maintenance:	$5 M	$5 M	$10 M	$15 M
	Amortize (Yrs):	20 yrs	20 yrs	20 yrs	20 yrs
	Cost of $ (%):	6%	6%	6%	5%
Floor Layout	Sections:	1	1	1	2
	Rows per Section:	1	1	10	10
	Cabinets per Row:	1	10	10	10
Server	Qty/Cabinet:	40	40	40	40
	Avg $ each:	$6000	$6000	$4000	$4000
	Amortize (Yrs):	5	5	3	3
Network and Optical-cable Costs	Network Type	TOR	TOR	TOR	TOR
	Qty/Cabinet:	=(Sections * Rows/Sections * Cabinets/Row)			
	TOR Switch avg $/ea.:	$5000	$5000	$2500	$2500
	Amortize (Yrs):	5	5	3	3
	Gbps:	10, 40, 100	10, 40, 100	10, 40, 100	10, 40, 100
	Max Bandwidth/User	10 Mbps	25 Mbps	50 Mbps	100 Mbps
	Network efficiency:	60%	60%	60%	60%
	50/125 OM3 $/m:	[10G@$1.25/m , 40G@$2.5/m, 100G@$3.25/m]			
	50/125 OM4 $/m:	[10G@$2.00/m , 40G@$4.25/m, 100G@$6.50/m]			
Genetic Algorithm Parameters	Population:	50	50	100	150
	Max Generations:	100	100	150	200
	Stall Generations Limit	150	150	150	200
	Cross over Fraction:	60%	70%	70%	80%
	Pareto Fraction:	60%	70%	70%	80%
	Mutation	@Gaussian Distribution function (Appendix 5.1)			
	Crossover Function:	@Arithmetic function (Appendix 5.1)			

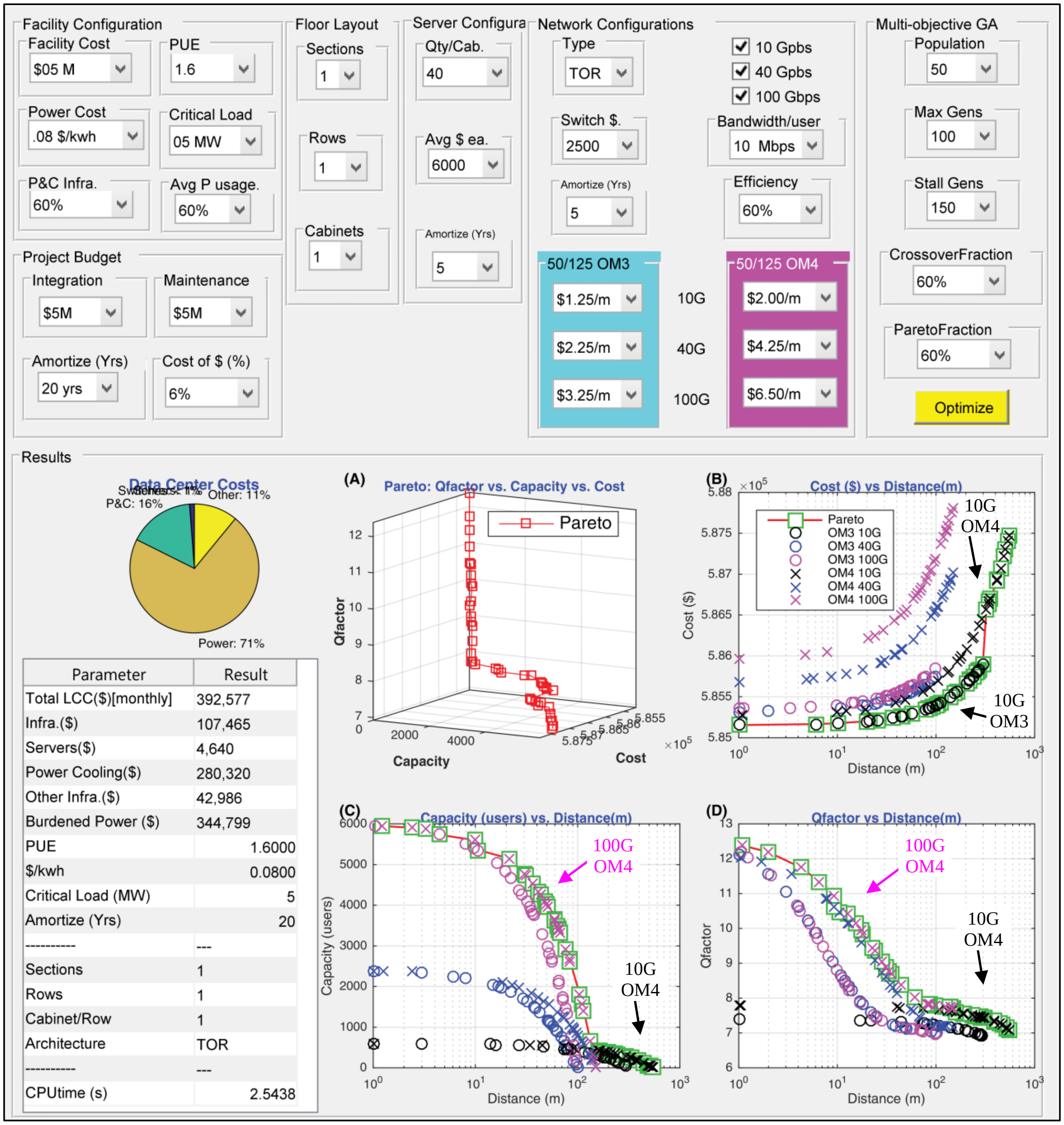
The model assumes 2 fiber-optics ports per server, with each port supporting the corresponding 10G, 40G, and 100G bandwidth, two TOR switches per cabinet, and each server utilizing the same optical fiber as the network design. The Parteo front results are shown in a 3D space view and presented with a bi-objective projection of the X-Y, X-Z, and Y-Z axes of each parameter versus measures of distance. Costs are sourced from industry leading solution providers [31], [32].

In the following section is presented the results and discussion of the four case studies.

3.6 Case 1: 1S.1R.1C

3.6.1 Results

Shown in Figure 3.4 below is the result of the analysis for Case Study 1 with the table of results for the data center costs and four Parteo Frontier subplots consisting of one 3D view and three bi-objective views.



Facility Configuration
Facility Cost: $05 M
PUE: 1.6
Power Cost: .08 $/kwh
Critical Load: 05 MW
P&C Infra.: 60%
Avg P usage.: 60%

Project Budget
Integration: $5M
Maintenance: $5M
Amortize (Yrs): 20 yrs
Cost of $ (%): 6%

Floor Layout
Sections: 1
Rows: 1
Cabinets: 1

Server Configura
Qty/Cab.: 40
Avg $ ea.: 6000
Amortize (Yrs): 5

Network Configurations
Type: TOR
Switch $.: 2500
Amortize (Yrs): 5
☑ 10 Gpbs
☑ 40 Gpbs
☑ 100 Gbps
Bandwidth/user: 10 Mbps
Efficiency: 60%

	50/125 OM3	50/125 OM4
10G	$1.25/m	$2.00/m
40G	$2.25/m	$4.25/m
100G	$3.25/m	$6.50/m

Multi-objective GA
Population: 50
Max Gens: 100
Stall Gens: 150
CrossoverFraction: 60%
ParetoFraction: 60%

Results

Parameter	Result
Total LCC($)[monthly]	392,577
Infra.($)	107,465
Servers($)	4,640
Power Cooling($)	280,320
Other Infra.($)	42,986
Burdened Power ($)	344,799
PUE	1.6000
$/kwh	0.0800
Critical Load (MW)	5
Amortize (Yrs)	20
----------	---
Sections	1
Rows	1
Cabinet/Row	1
Architecture	TOR
----------	---
CPUtime (s)	2.5438

Figure 3.4: Case Study 1 Inputs and Pareto Frontier Results

3.6.2 Discussion

In Figure 3.4 above, evaluating the Case 1 pie chart for data center costs and the table of results, we observe that the cost of power and cooling dominates at cumulative 87% of the monthly budget. This is to be expected given that the entire infrastructure for this case is supporting only cabinet. These results illustrate the overwhelming impact that the cost of power has on an empty data center. With a $5M million amortized facility cost, the overwhelming long-term cost is that of the power cooling and burdened power, while the amortized cost of the servers and networking equipment is negligible relative to the overall cost.

From the optical network Pareto analysis presented in the subplots, several observations are drawn:

Subplot (A) - Q-factor vs Capacity vs Cost: The general trend is a decreasing and winding Parteo front with an initial steep descent and then a longer wiggling taper.

Subplot (B) – Cost ($) vs Distance (m): The objective function is to minimize cost (y-axis), therefore the Pareto front is determined on the underside of the bi-objective solution space. We observe that the 10G OM4 dominates at the long distances and trade-off for higher costs ($\$5.875 \times 10^5$ to $\$5.865 \times 10^5$), and that 10G OM3 dominates at lower distance with a trade-off for lower cost (<$\$5.86 \times 10^5$).

Subplot (C) – Q-factor vs. Cost: The objective function is to maximize capacity of users (y-axis), therefore the Pareto front is determined on the topside of the bi-objective solution space. We observe that the 100G OM4 dominates at the shorter distances with a trade-off for higher capacity (6000 to 750), and that 10G OM3 dominates at longer distance with a trade-off for lower capacity (<750).

Subplot (D) – Q-factor vs. Capacity: The objective function is to maximize Q-factor (y-axis), therefore the Pareto front is determined on the topside of the bi-objective solution space. We observe that at 10 Mbps per user (.01 Gbps), the 100G OM4 dominates at the shorter distances with trade-off for higher Q-factor (12.5 to 7.75), and that 10G OM3 dominates at longer distance with a trade-off for lower Q-factor (<7.75).

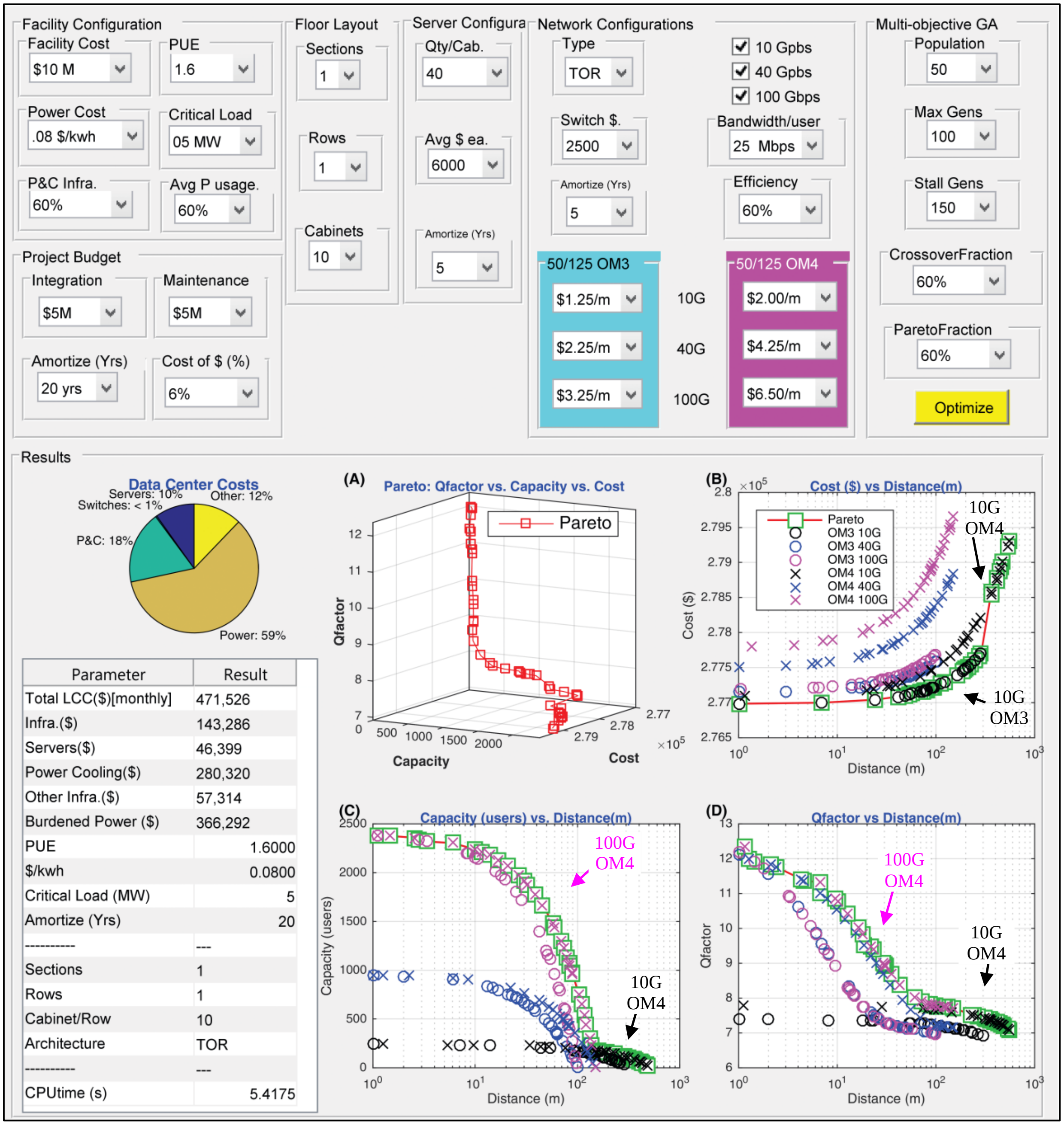
3.6.3 Observations

For considerations of lower cost, the 10G OM4 and 10G OM3 are optimal. For consideration of capacity and Q-factor, the 100G OM4 dominates at shorter distance and the 10G OM4 at longer distance. Lastly, the GPU-enabled vectorized multi-objective genetic algorithm solved the problem in 2.76 seconds.

3.7 Case 2: 1S.1R.10C

3.7.1 Results

Shown in Figure 3.5 below is the result of the analysis for Case Study 2 with the table of results for the data center costs and four Parteo Frontier subplots consisting of one 3D view and three bi-objective views.



Facility Configuration
Facility Cost: $10 M
PUE: 1.6
Power Cost: .08 $/kwh
Critical Load: 05 MW
P&C Infra.: 60%
Avg P usage.: 60%

Project Budget
Integration: $5M
Maintenance: $5M
Amortize (Yrs): 20 yrs
Cost of $ (%): 6%

Floor Layout
Sections: 1
Rows: 1
Cabinets: 10

Server Configura
Qty/Cab.: 40
Avg $ ea.: 6000
Amortize (Yrs): 5

Network Configurations
Type: TOR
Switch $.: 2500
Amortize (Yrs): 5
☑ 10 Gpbs
☑ 40 Gpbs
☑ 100 Gbps
Bandwidth/user: 25 Mbps
Efficiency: 60%

	50/125 OM3	50/125 OM4
10G	$1.25/m	$2.00/m
40G	$2.25/m	$4.25/m
100G	$3.25/m	$6.50/m

Multi-objective GA
Population: 50
Max Gens: 100
Stall Gens: 150
CrossoverFraction: 60%
ParetoFraction: 60%

Results

Parameter	Result
Total LCC($)[monthly]	471,526
Infra.($)	143,286
Servers($)	46,399
Power Cooling($)	280,320
Other Infra.($)	57,314
Burdened Power ($)	366,292
PUE	1.6000
$/kwh	0.0800
Critical Load (MW)	5
Amortize (Yrs)	20
----------	---
Sections	1
Rows	1
Cabinet/Row	10
Architecture	TOR
----------	---
CPUtime (s)	5.4175

Figure 3.5: Case Study 2 Inputs and Pareto Frontier Results

3.7.2 Discussions

In Figure 3.5 above, evaluating the Case 2 pie chart for data center costs and the table of results, once again, the dominant cost to run the data center is the power, which is driven by the 1.6 PUE requirement and the $.08 kWh rate to power 10 cabinets loaded with 40 servers in each cabinet. The power is consuming in excess of 77% of the monthly budget and followed by the cost of the servers, 10%, when amortized over a 5 year time. The cost for the switches, the optical network, and the other infrastructure is at ~13%. These results demonstrate the significant impact that power exerts on the financial budget.

From the optical network Pareto analysis presented in the subplots, several observations are drawn:

Subplot (A) - Q-factor vs Capacity vs Cost: The general trend is a decreasing and winding Parteo front with an initial steep descent and then a longer wiggling taper.

Subplot (B) – Cost ($) vs Distance (m): The objective function is to minimize cost (y-axis), therefore the Pareto front is determined on the underside of the bi-objective solution space. We observe that the 10G OM4 dominates at the long distances and trade-off for higher costs ($2.79 x 10^5 to $2.783 x 10^5), and that 10G OM3 dominates at lower distance with a trade-off for lower cost (<$2.78 x 10^5) .

Subplot (C) – Q-factor vs. Cost: The objective function is to maximize capacity of users (y-axis), therefore the Pareto front is determined on the topside of the bi-objective solution space. We observe that at 25 Mbps per user (.025 Gbps), the 100G OM4 dominates at the shorter distances with a trade-off for higher capacity (2400 to 250), and that 10G OM3 dominates at longer distance with a trade-off for lower capacity (<250).

Subplot (D) – Q-factor vs. Capacity: The objective function is to maximize Q-factor (y-axis), therefore the Pareto front is determined on the topside of the bi-objective solution space. We observe that the 100G OM4 dominates at the shorter distances with trade-off for higher Q-factor (12.25 to 7.8), and that 10G OM3 dominates at longer distance with a trade-off for lower Q-factor (<7.8).

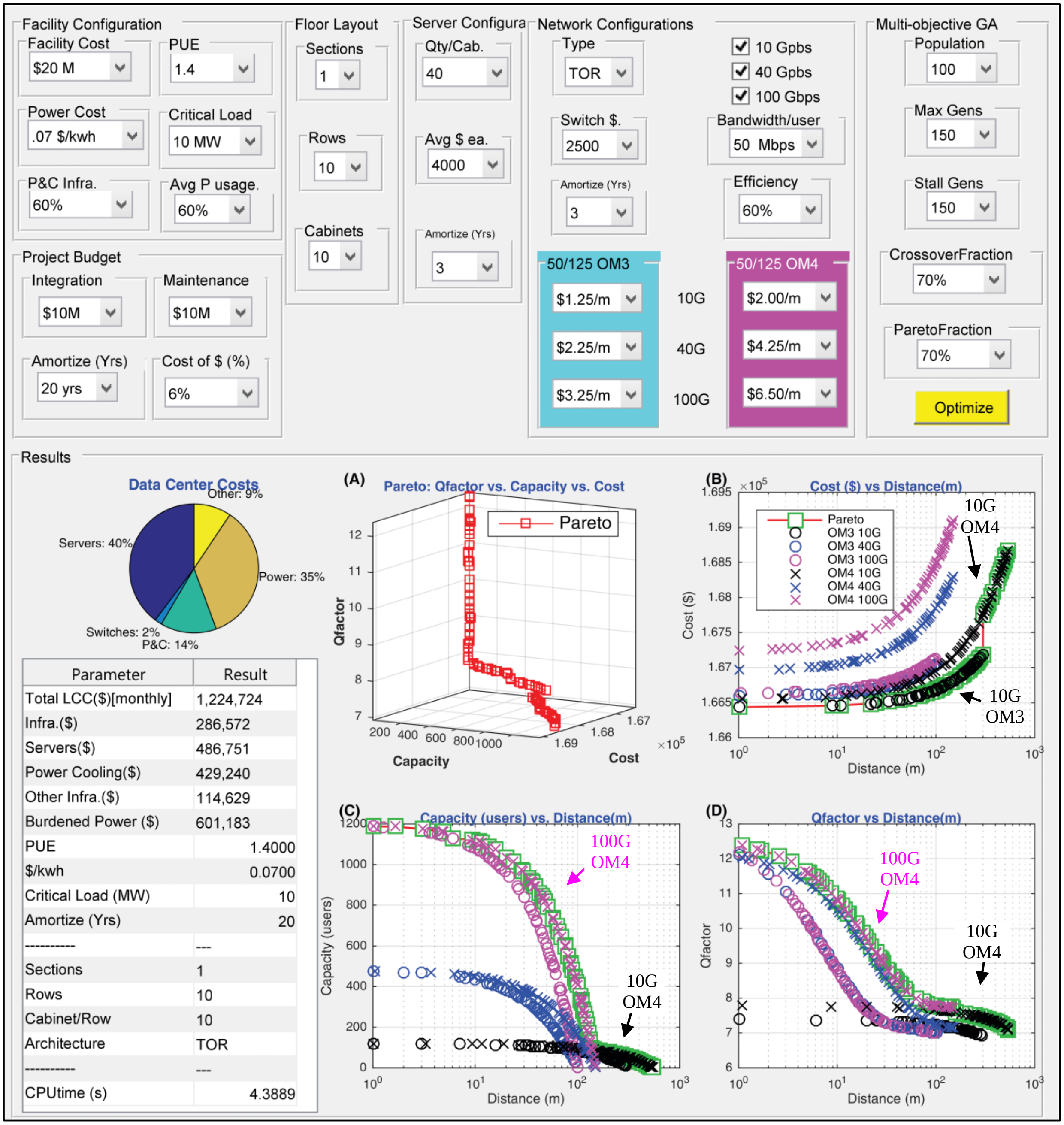
3.7.3 Observations

For considerations of lower cost, the 10G OM4 and 10G OM3 are optimal. For consideration of capacity and Q-factor, the 100G OM4 dominates at shorter distance and the 10G OM4 at longer distance. Lastly, the GPU-enabled vectorized multi-objective genetic algorithm solved the problem in 4.2792 seconds.

3.8 Case 3: 1S.10R.10C

3.8.1 Results

Shown in Figure 3.6 below is the result of the analysis for Case Study 3 with the table of results for the data center costs and four Parteo Frontier subplots consisting of one 3D view and three bi-objective views.



Facility Configuration
Facility Cost: $20 M
PUE: 1.4
Power Cost: .07 $/kwh
Critical Load: 10 MW
P&C Infra.: 60%
Avg P usage.: 60%

Project Budget
Integration: $10M
Maintenance: $10M
Amortize (Yrs): 20 yrs
Cost of $ (%): 6%

Floor Layout
Sections: 1
Rows: 10
Cabinets: 10

Server Configura
Qty/Cab.: 40
Avg $ ea.: 4000
Amortize (Yrs): 3

Network Configurations
Type: TOR
Switch $.: 2500
Amortize (Yrs): 3
☑ 10 Gpbs
☑ 40 Gpbs
☑ 100 Gbps
Bandwidth/user: 50 Mbps
Efficiency: 60%

	50/125 OM3	50/125 OM4
10G	$1.25/m	$2.00/m
40G	$2.25/m	$4.25/m
100G	$3.25/m	$6.50/m

Multi-objective GA
Population: 100
Max Gens: 150
Stall Gens: 150
CrossoverFraction: 70%
ParetoFraction: 70%

Results

Parameter	Result
Total LCC($)[monthly]	1,224,724
Infra.($)	286,572
Servers($)	486,751
Power Cooling($)	429,240
Other Infra.($)	114,629
Burdened Power ($)	601,183
PUE	1.4000
$/kwh	0.0700
Critical Load (MW)	10
Amortize (Yrs)	20
----------	---
Sections	1
Rows	10
Cabinet/Row	10
Architecture	TOR
----------	---
CPUtime (s)	4.3889

Figure 3.6: Case Study 3 Inputs and Pareto Frontier Results

3.8.2 Discussions

In Figure 3.6 above, evaluating the Case 3 pie chart for data center costs and the table of results, the dominant cost continues to be the power to run the facility which is driven by the 1.4 PUE requirement and the $.07 kWh rate to power 100 cabinets loaded with 40 servers in each cabinet. The power and cooling costs are consuming 49% of the monthly budget and followed by the cost of the servers, 40%, when amortized over 3 years. The cost for the switches, the optical network, and the other infrastructure are at 11%. These results show the importance of considering the long-term aspect of the recurring power costs.

From the optical network Pareto analysis presented in the subplots, several observations are drawn:

Subplot (A) - Q-factor vs Capacity vs Cost: The general trend is a decreasing and winding Parteo front with an initial steep descent and then a longer wiggling taper.

Subplot (B) – Cost ($) vs Distance (m): The objective function is to minimize cost (y-axis), therefore the Pareto front is determined on the underside of the bi-objective solution space. We observe that the 10G OM4 dominates at the long distances and trade-off for higher costs ($\$1.688 \times 10^5$ to $\$1.673 \times 10^5$), and that 10G OM3 dominates at lower distance with a trade-off for lower cost ($<\$1.673 \times 10^5$),.

Subplot (C) – Q-factor vs. Cost: The objective function is to maximize capacity of users (y-axis), therefore the Pareto front is determined on the topside of the bi-objective solution space. We observe that at 50 Mbps per user (.05 Gbps), the 100G OM4 dominates at the shorter distances with a trade-off for higher capacity (1200 to 100), and that 10G OM3 dominates at longer distance with a trade-off for lower capacity (<100).

Subplot (D) - Qfactor vs. Capacity: The objective function is to maximize Q-factor (y-axis), therefore the Pareto front is determined on the topside of the bi-objective solution space. We observe that the 100G OM4 dominates at the shorter distances with trade-off for higher Q-factor (12.5 to 7.5), and that 10G OM3 dominates at longer distance with a trade-off for lower Q-factor (<7.5).

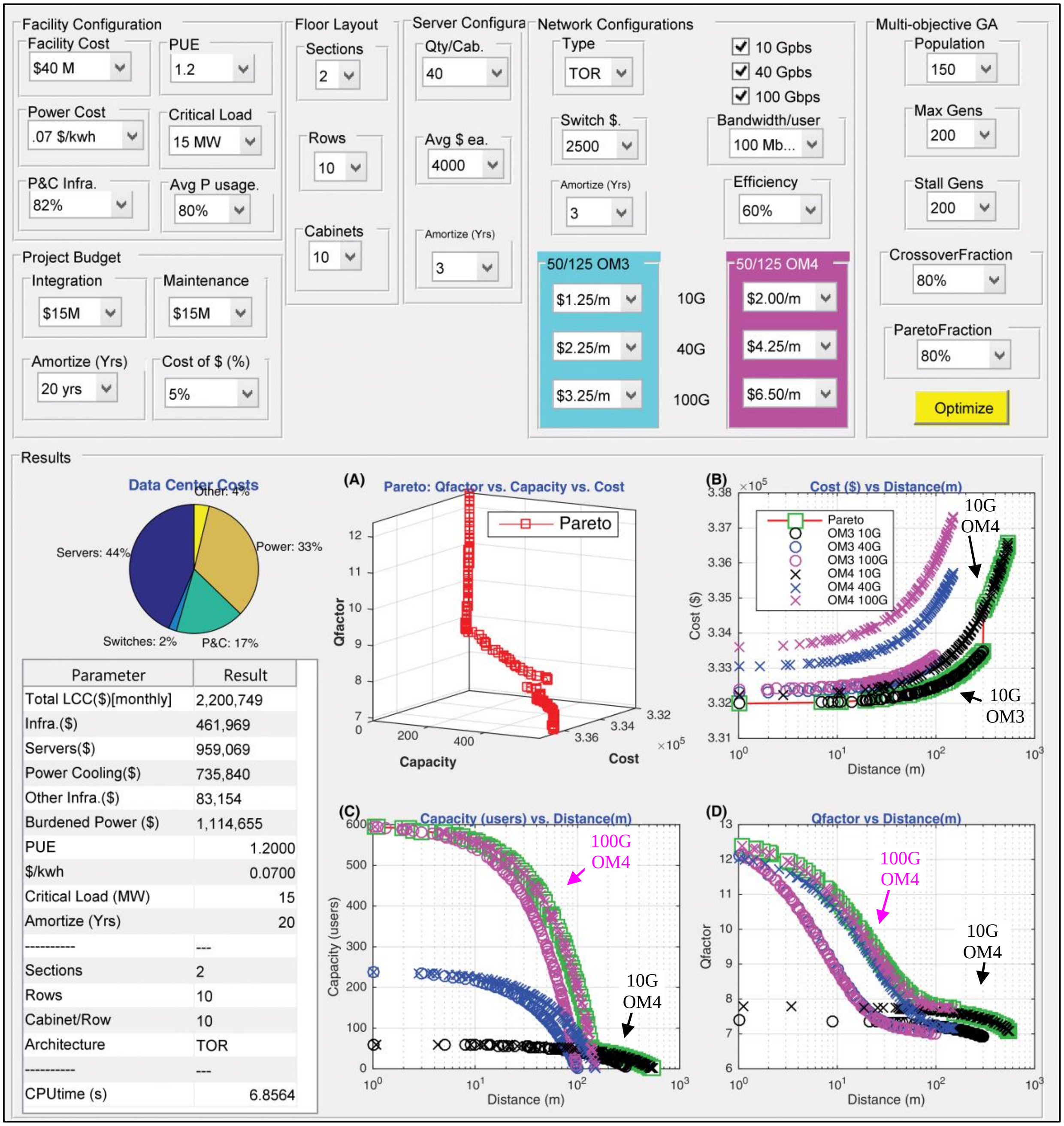
3.8.3 Observations

For considerations of lower cost, the 10G OM4 and 10G OM3 are optimal. For consideration of capacity and Qfactor, the 100G OM4 dominates at shorter distance and the 10G OM4 at longer distance. Lastly, the GPU-enabled vectorized multi-objective genetic algorithm solved the problem in 4.5069 seconds.

3.9 Case 4: 2S.10R.10C

3.9.1 Results

Shown in Figure 3.7 below is the result of the analysis for Case Study 4 with the table of results for the data center costs and four Parteo Frontier subplots consisting of one 3D view and three bi-objective views.



Facility Configuration
Facility Cost: $40 M
PUE: 1.2
Power Cost: .07 $/kwh
Critical Load: 15 MW
P&C Infra.: 82%
Avg P usage.: 80%

Project Budget
Integration: $15M
Maintenance: $15M
Amortize (Yrs): 20 yrs
Cost of $ (%): 5%

Floor Layout
Sections: 2
Rows: 10
Cabinets: 10

Server Configura
Qty/Cab.: 40
Avg $ ea.: 4000
Amortize (Yrs): 3

Network Configurations
Type: TOR
☑ 10 Gpbs
☑ 40 Gpbs
☑ 100 Gbps
Switch $.: 2500
Bandwidth/user: 100 Mb...
Amortize (Yrs): 3
Efficiency: 60%

50/125 OM3		50/125 OM4
$1.25/m	10G	$2.00/m
$2.25/m	40G	$4.25/m
$3.25/m	100G	$6.50/m

Multi-objective GA
Population: 150
Max Gens: 200
Stall Gens: 200
CrossoverFraction: 80%
ParetoFraction: 80%

Results

Parameter	Result
Total LCC($)[monthly]	2,200,749
Infra.($)	461,969
Servers($)	959,069
Power Cooling($)	735,840
Other Infra.($)	83,154
Burdened Power ($)	1,114,655
PUE	1.2000
$/kwh	0.0700
Critical Load (MW)	15
Amortize (Yrs)	20
----------	---
Sections	2
Rows	10
Cabinet/Row	10
Architecture	TOR
----------	---
CPUtime (s)	6.8564

Figure 3.7: Case Study 4 Inputs and Pareto Frontier Results

3.9.2 Discussion

In Figure 3.7 above, evaluating the Case 4 pie chart for data center costs and the table of results, the dominant cost is the power to run the facility which is driven by the 1.2 PUE requirement and the $.07 kWh rate to power 200 cabinets loaded with 40 servers in each cabinet. The cumulative power and cooling is consuming 50% of the monthly budget and followed by the cost of the servers, 44%, when amortized over a 3 year time. The cost for the switches, the optical network, and the other infrastructure is relatively low, at 6%. These results demonstrate the importance of considering the long-term aspect of the recurring power costs for a large data center, which appears to overcome the initial infrastructure and project management costs. It is apparent that when considering the site selection for a data center, that the long-term negotiated market rate for power needs to be at the forefront of the strategy.

From the optical network allocating 100 megabits/s to each user, several observations are drawn:

Subplot (A) - Q-factor vs Capacity vs Cost: The general trend is a decreasing and winding Parteo front with an initial steep descent and then a longer wiggling taper.

Subplot (B) – Cost ($) vs Distance (m): The objective function is to minimize cost (y-axis), therefore the Pareto front is determined on the underside of the bi-objective solution space. We observe that the 10G OM4 dominates at the long distances and trade-off for higher costs ($3.37 x 10^5 to $3.35 x 10^5), and that 10G OM3 dominates at lower distance with a trade-off for lower cost (<$3.335 x 10^5),.

Subplot (C) – Q-factor vs. Cost: The objective function is to maximize capacity of users (y-axis), therefore the Pareto front is determined on the topside of the bi-objective solution space. We observe that at 100 Mbps per user (.1 Gbps), the 100G OM4 dominates at the shorter distances with a trade-off for higher capacity of simultaneous users saturating the network (600 to 75), and that 10G OM3 dominates at longer distance with a trade-off for lower simultaneous users (<75) saturating the network.

Subplot (D) - Qfactor vs. Capacity: The objective function is to maximize Q-factor (y-axis), therefore the Pareto front is determined on the topside of the bi-objective solution space. We observe that the 100G OM4 dominates at the shorter distances with trade-off for higher Q-factor (12.5 to 7.5), and that 10G OM3 dominates at longer distance with a trade-off for lower Q-factor (<7.5).

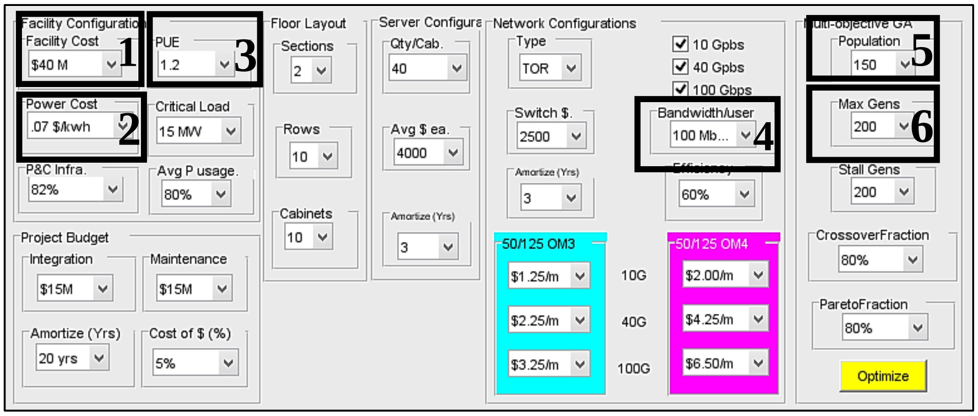
3.9.3 Observations

For considerations of lower cost, the 10G OM4 and 10G OM3 are optimal. For consideration of capacity and Qfactor, the 100G OM4 dominates at shorter distance and the 10G OM4 at longer distance. Lastly, the GPU-enabled vectorized multi-objective genetic algorithm solved the problem in 7.2526 seconds.

3.10 Sensitivity Analysis

3.10.1 Framework

Utilizing the Case 4 parameters as the base for performing sensitivity analysis, the following parameters were studied: 1) Facility Costs, 2) Power Cost, 3) PUE, and, 4) Bandwidth per User on the Life-Cycle Costs, and 5) Genetic Algorithm Population and 6) Genetic Algorithm Maximum Generations on cputime.



Facility Cost $40 M
PUE 1.2
Power Cost .07 $/kwh
Critical Load 15 MW
P&C Infra. 82%
Avg P usage. 80%
Integration $15M
Maintenance $15M
Amortize (Yrs) 20 yrs
Cost of $ (%) 5%
Sections 2
Rows 10
Cabinets 10
Qty/Cab. 40
Avg $ ea. 4000
Amortize (Yrs) 3
Type TOR
Switch $. 2500
Amortize (Yrs) 3
☑ 10 Gpbs
☑ 40 Gpbs
☑ 100 Gbps
Bandwidth/user 100 Mb...
Efficiency 60%
10G $1.25/m $2.00/m
40G $2.25/m $4.25/m
100G $3.25/m $6.50/m
Population 150
Max Gens 200
Stall Gens 200
CrossoverFraction 80%
ParetoFraction 80%

Figure 3.8: Parameters explored for Sensitivity Analysis

3.10.2 Facility Costs, Power Costs, and PUE

In Table 3.4 below is presented the results for the sensitivity analysis study of the facility costs, powers costs and the PUE. Each of the parameters was individually explored as a single independent variable to study the effect on the mothly life-cycle costs.

Table 3.4: Sensitivity Analysis for Facility Costs, Power Costs, and PUE

Facility	% Change	LCC $ [monthly]	% Change	Power Cost	% Change	LCC $ [monthly]	% Change	PUE	% Change	LCC $ [monthly]	% Change
$ 5	-80%	1.97E+06	-6%	.04	-33%	1.89E+06	-10%	1.0	-33%	2.08E+06	-13%
$ 10	-60%	2.00E+06	-5%	.05	-17%	1.99E+06	-5%	1.2	-20%	2.20E+06	-8%
$ 20	-20%	2.07E+06	-2%	.06	0%	2.10E+06	0%	1.4	-7%	2.32E+06	-3%
$ 25	0%	2.10E+06	0%	.07	17%	2.20E+06	5%	1.5	0	2.38E+06	0
$ 30	20%	2.13E+06	2%	.08	33%	2.31E+06	10%	1.6	7%	2.45E+06	3%
$ 40	60%	2.20E+06	5%					1.8	20%	2.57E+06	8%
$ 45	80%	2.23E+06	6%					2.0	33%	2.69E+06	13%

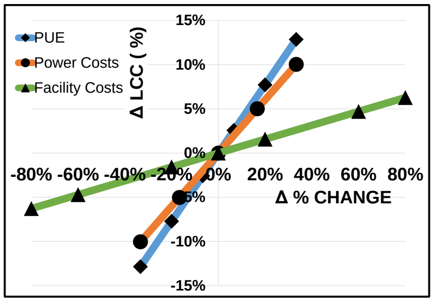


Figure 3.9: Sensitivity Analysis for Facility Costs, Power Costs, and PUE

As shown in Figure 3.9 above, small changes in PUE and Power Costs yield the most impact to LCC.

Presented in Figure 3.10 below are the sensitivity analysis results for evaluating the effects of increasing Bandwidth per User at 10, 20, 30, 40, and 50 MB/s – recall that 50 Megabyte/s = .4 Gigabit per second (Gbps) = 400 Megabit per second (Mbps). The 3D Pareto frontier is displayed, along with the optimal solutions versus measures of distance (X=OM4, O=OM3**, magenta=100G**, **blue=40G**, and **black=10G**).

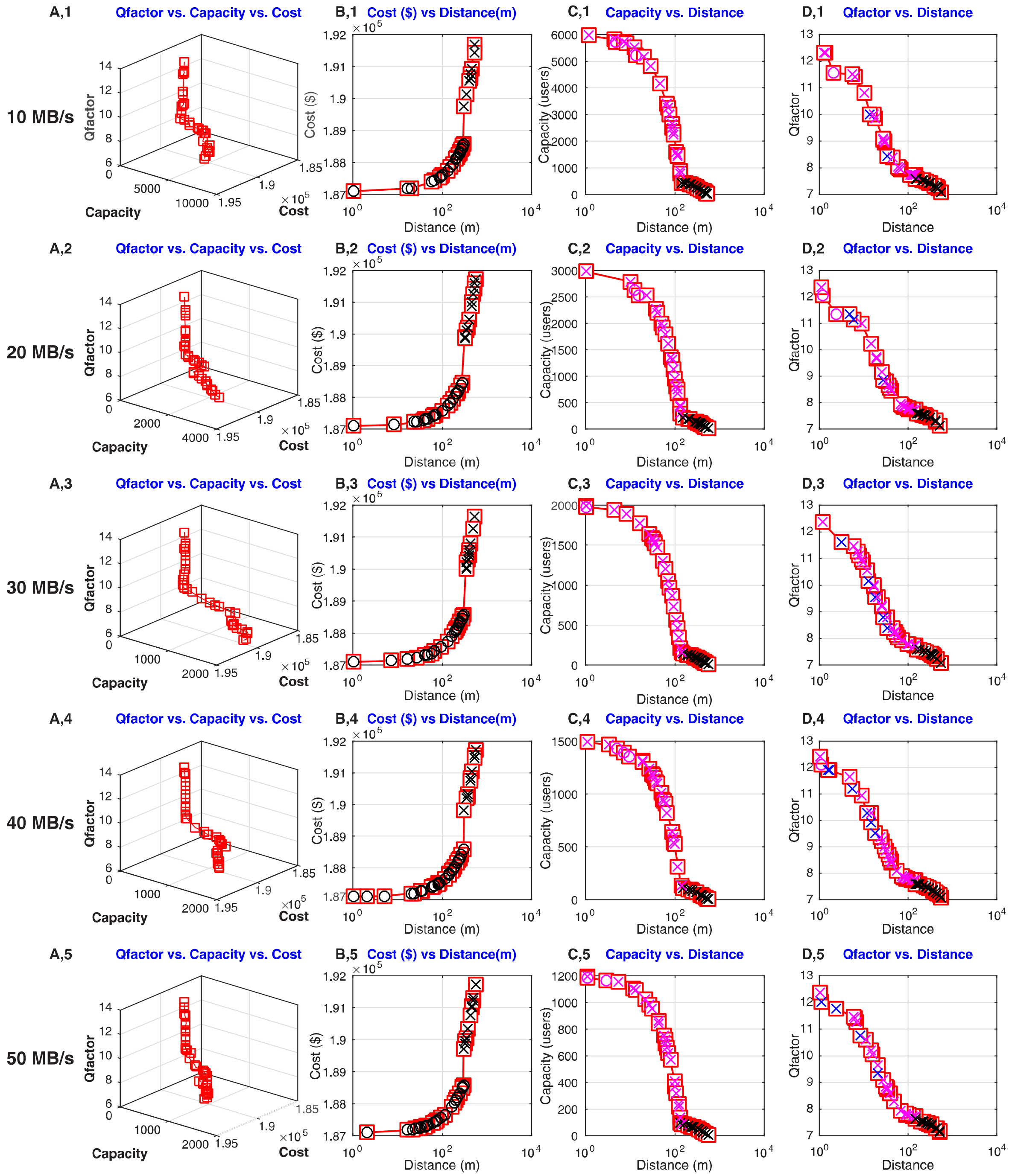


Figure 3.10: Sensitivity Analysis for Bandwidth per User [10, 20, 30, 40, 50] MB/s

We observe two key aspects of the bandwidth sensitivity: 1) 100G OM4 is a dominant solution with respect to capacity and Q-factor; and 2) 10G OM4 and OM3 prevail at lower cost and at longer distance reach .

3.10.3 Genetic Algorithm Parameters

The genetic algorithm heuristic relies on a probabilistic distribution for random selection and mutation. The consequences for using genetic algorithms are two-fold: 1) Numerical results will vary for each run, and 2) Cputime will increase with the growing sample size for the Population and Max Generations.

Presented in Table 3.5 and Table 3.6 below are the results of the sensitivity analysis for evaluating the change in genetic algorithm (1) Population Size and (2) Max Generations on the impact of computation time. Each table includes the cputime for three sequential runs and the average of the runs is plotted. The purpose for the three runs is to demonstrate that variance influences not only in the numerical results, but also in the computational time, as a result of the randomness of the algorithm.

Table 3.5: Sensitivity Analysis of Genetic Algorithm Population Size on CPUtime

Population	CPUtime1	CPUtime2	CPUtime3	Average
50	4.3481	4.232	4.2154	4.2652
100	5.4870	5.4648	5.4406	5.4641
150	7.0222	7.081	7.0393	7.0475
200	8.9566	8.9932	8.9893	8.9797

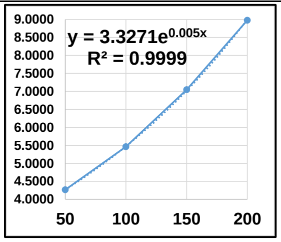
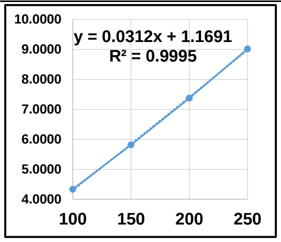


Table 3.6: Sensitivity Analysis of Genetic Algorithm Generations on CPUtime

Generations	CPUtime1	CPUtime2	CPUtime3	Average
100	4.3111	4.3248	4.3620	4.3326
150	5.8284	5.8128	5.8044	5.8152
200	7.3737	7.4326	7.3202	7.3755
250	9.0424	8.9530	9.0606	9.0187



From Table 3.5 and Table 3.6, as the size of Population and Max Generation increase, we observe steep increases in cputime. In this work, vectorization and a GPU (discussed in Section 2.6 above) are both utilized to help reduce the processing time of the ranking and indexing of the Pareto frontier fitness values using the MATLAB Arrayfun and Bxsfun functions (Appendix 5.1). The increase in Population Size increases cputime exponentially, while the increase in max generation is shown to increase cputime linearly.

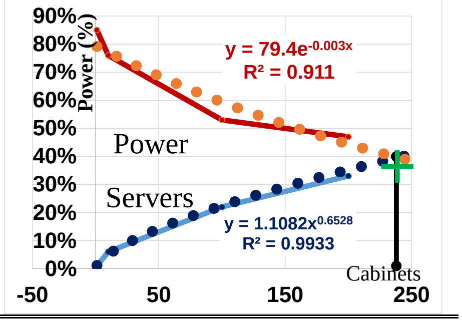
In summary, the sensitivity analysis of two genetic algorithm parameter shows that increasing Population Size has the steepest impact to cputime and the randomness of the heuristic permeates to cputime. Therefore, it is important to run the analysis several times and utilize an average of result values.

3.11 Summary of Simulation and Numerical Analysis

In Table 3.7 below is presented a summary of the data center costs analysis from the four case studies. We observe that as the data center increases in size (i.e., number of cabinets), the cost for the power outweighs the cumulative amortized cost of the infrastructure, servers in the racks, and networking infrastructure.

Table 3.7: Summary of Case Study Data Center Costs (%)

	Case 1 1S.1R.1C	Case 2 1S.1R.10C	Case 3 1S.10R.10C	Case 4 2S.10R.10C
Power:	85%	76%	56%	47%
Power Cooling Infrastructure:	9%	10%	12%	12%
Servers:	<1%	6%	22%	30%
TOR:	<1%	1%	2%	2%
Other:	6%	7%	8%	8%



As the size of the data center increases, efficiency is gained from economies of scale for the Power and Cooling Infrastructure investments. In the model developed in this work, the cost of servers filling the racks grows at such a rate that, through a regression forecast, will cost as much as the power at 238 fully loaded cabinets. We learn that data center managers should not only consider the cost of the infrastructure and power, but also forecast the costs of saturating the cabinets with equipment to forecast break-even.

The Pareto frontier is a trade-off curve of the non-dominated solutions, meaning that one solution along the curve is not better than another, allowing a decision-manager to evaluate the trade-offs. In Table 3.8 below is presented a summary of the ‘frequency count’ for the optical fiber-type from the Pareto optimal solutions from the bandwidth per user sensitivity analysis, defined in Figure 3.10 above.

Table 3.8: Summary of Pareto Frontier Frequency for Sensitivity of Bandwidth per User

Solution		Cost vs Distance					Capacity vs. Distance					Qfactor vs Distance						
Class	Marker	10	20	30	40	50	10	20	30	40	50	10	20	30	40	50	Freq.	%
10G OM3	**O**	22	22	22	24	22	0	0	0	0	0	0	0	0	0	0	112	20%
40G OM3	**O**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
100G OM3	O	0	0	0	0	0	2	2	2	0	3	1	1	0	0	1	12	2%
10G OM4	**X**	11	13	9	8	10	14	16	18	14	15	18	12	11	14	16	119	**35%**
40G OM4	**X**	0	0	0	0	0	0	0	1	0	0	1	2	3	2	6	15	3%
100G OM4	**X**	0	0	0	0	0	22	23	21	23	23	24	24	24	24	24	232	41%

The intent of presenting frequency count is to help elicit which of the Pareto optimal solution classes are the most dominant of the non-dominated solutions; in the spirit of Darwin’s theory of natural selection [97] and Mendel’s theory on genetics [98], these are the ‘alpha-males’ on the MOGA Pareto curve. In this work, the 100G OM4 is shown to be the alpha-male, with a 41% overall frequency on the Pareto curves. The 10G OM4 solutions are useful for low user capacity and long-reach requirements, and show up 35%.

In the next section, is a discussion on the concluding thoughts and recommendations for the future.

4 Conclusion and Recommendations

Presented henceforth is the summary of the findings, insights, and recommendations, as they pertain to the questions posed in Section 1.2: Research Objectives of this thesis, and restated below:

1. What are the key attributes needed to build a data center fiber-optic network?
2. What are the important factors for considering Pareto optimal data center fiber-optic networks?
3. How should data center vendor's best respond to new technology platforms?
4. How can data center providers address future commoditization of the infrastructure?
5. What skills will be important for the future-of-work to manage data center services?
6. What is the next phase of evolution for data center optical network design?

4.1 Q1: What are the key attributes needed to build a data center fiber-optic network?

Findings: One of the most interesting and relative findings is understanding the impact of PUE and power costs ($/kWh) on the total life-cycle costs. We identify through the simulation that small changes in PUE and Power Cost can have steep impact to the life-cycle costs, far exceeding those incurred from the initial infrastructure costs. The key results that we learn from the numerical analysis of the data center cost modeling is that an impactful parameter that data center decision-makers must contend with is: cost of power. Another finding is that when evaluated simultaneously for capacity, Q-factor, and cost, the 100G OM4 provides a champion solution. The 40G solution is shown to be useful as a gap-fill, and in most cases, pursuing the 100G solution is more optimal. For longer distances, or needs requiring low user capacity, the 10G solution is optimal.

Insights: The research performed in this thesis leads us to understand that from a strategic perspective we need to migrate towards TOR in order to facilitate the expansion towards 100G and 400G. This will become especially important once the tipping point for the economic value of the OM3 multi-mode fiber shifts to OM4 multi-mode fiber, and even more so should single-mode fiber become the new norm for short-reach applications using a Wavelength Multi-plexing method [61].

Recommendation: From the perspective of cost savings from the power, it is recommended to maintain the data center temperature calibrated to operate as close as possible to the maximum temperature specification of the equipment. Just a few percentage points in cost savings incurred from power can have substantial long-term benefit on the life-cycle costs. The shift towards 4x25G and 10x10G is evident in the forward product roadmaps so ensuring that the data center designs of infrastructure will support the forthcoming software-defined parallel-optical networks is vital to the long-term success of the strategy.

4.2 Q2: What are the important factors for considering Pareto optimal data center fiber-optic networks?

Findings: The use of TOR networks is most efficient towards expanding to 100G and 400G overcoming the messy and complicated cabling of EOR which contributes to higher operational expenses in the data center as the staff hours required to manage the cabling increase. As the quantity of servers grows, not only the cost escalates but also the chance for errors in the inter-connections, causing network downtime.

The optimal network should be designed to a minimal Q-factor of 7 to ensure less than a 10^{-12} bit error rate. Optical fiber supports different tiers of user capacity and maximum distance, with 10G supporting lower capacity and longer distances, up to the 100G which supports high capacity and short distances. Though evaluating the 100G, from a myopic point of view of $/meter, is concerning due to a high per unit cost, expanding the view to consider a multi-objective perspective, we observe that the bandwidth capacity is orders of magnitude higher than other solutions while sustaining >7 Q-factor. Therefore, we find that effective evaluation of data center optical networks is performed with simultaneous trade-off analysis of life-cycle costs, capacity, and Q-factor; which is efficiently conducted using 3D Pareto frontier analysis. For the short reach and high capacity needs, implementing the 100G OM4 is the current 'alpha-male'. This work did not find Parteo optimal placement for the 40G solutions.

Insights: Using an integrated design with MSDO provides additional insights into evaluating optimal (i.e., non-dominated) solutions when considering three simultaneous objective functions: minimizing cost, maximizing capacity (users), and maximizing optical transmission quality (Q-factor). The important factors affecting total cost is power, capacity is the bandwidth, and Q-factor the optical fiber modal characteristics.

Recommendations: The main recommendation to consider is that the driving force for data center design should be predicated on obtaining the lowest kWh rate possible, as this will have the strongest long term benefit for minimizing the life-cycle costs. A strategy that seeks out and establishes stable and low cost rates for power will have the most benefit towards data center life-cycle reduction.

In terms of optical networks, for long reach and low user capacity needs, the 10G OM4 is an ideal implementation, while at short reach and high user capacity needs the recommendation is 100G OM4.

4.3 Q3: How should data center vendor's best respond to new technology platforms?

Findings: New technology follows an adoption lifecycle that is related to demand and cost. The most valuable technology are the ones that provide a rich ecosystem for the product platform, which includes not only the most energy efficient technology, but also the community of users to share ideas, technical support, warranty service, and case study example for implementation. The vendors that demonstrate the most success (e.g., Intel, Cisco, Corning, IBM, APC) are the ones that build ecosystems, not just products [120].

Insights: It has been demonstrated in this work that one of the major influences to data center life-cycle management is the cost of the power. Great efforts are exerted to keep the ambient temperature within the data center at the threshold of the equipment temperature specifications. It is understandable that vendors are constantly on the verge of the next great technology to reduce heat and/or be more energy efficient; the utopia point for a data center is one with zero heat.

Recommendations: The main recommendation for data center vendors is to understand that manager's need, besides technology that aims to keeps things cool, is access to data. The key to facilitating the role of data center managers is to develop hardware that is more energy efficient through improved cooling design, and, is more tightly integrated to software monitoring that allows data analysis from the logs. The products that give more control for automation and gaining insights from data analysis are the most useful.

4.4 Q4: How can data center providers address future commoditization of the infrastructure?

Findings: In this work, it has been demonstrated that initial costs for a data center, even when amortized over 20 years, requires substantial upfront capital. Data center designers will build-in optionality to expand and only develop the initial phases, allowing managers to exercise the expansion option in the future [121].

Insights: Vendors that are in business of selling computer/IT hardware, need to adapt the business models to providing leases of infrastructure, also known as Infrastructure as a Servers (IaaS), in which customers will no longer have to physically own the equipment, but rather may lease it based on the pro-rata amount of data that is moved, or another form of utilization.

Recommendations: Data center providers that shift towards an Infrastructure as a Servers (IaaS) can help: 1) move the budgeting from capital expenditures to operating expenditures which eases cost accounting, 2) allow for increased response to usage spikes, and 3) make growth more scalable. In the words of Infor's CEO Charles Phillips: "Friends don't let friends build data centers anymore."[112]

4.5 Q5: What skills will be important for the future-of-work to manage data center services?

Findings: The future will see more need for skills related to automation of services and to developing tools that assist in visualizing the systems utilization occurring within the data center. One of the most interesting findings to apply towards the future-of-work was identified during the IEEE-HPEC 2015 conference, which demonstrated the use of a virtual reality 3D game to visualize the utilization of a data center [113]. This trend identifies that the skills are shifting towards data analytics and programming of automatic services.

Insights: The managers of the data center will no longer need to be physically present like in the past, with many of the routine maintenance and management aspects controlled remotely. The two key skills that individuals will need include: 1) capabilities for scripting languages to automate tasks and 2) data analysis skills to mine data rich logs towards developing capacity planning insights.

Recommendations: Individuals interested in gaining employment or managing data centers will need to gain expertise with systems design, programming, multi-disciplinary optimization, and data visualization. The data center is quickly becoming a unified infrastructure that is almost entirely automated for control. To succeed in a role of managing a data center, gaining experience with systems automation is paramount.

4.6 Q6: What is the next phase of evolution for data center optical network design?

Findings: As originally introduced to the author of this work during an interview with Mark Silis, Associate VP of MIT IS&T (April 8th, 2015), the future of the optical networking will move to software defined networks. This finding was further substantiated by Neela Jacques, Executive Director, OpenDaylight at the DatacenterDynamics Converged conference, in which he identified that software-defined networking will allow for easier identification and tracking of issues through an open framework of development [114]. To add to this future trend, John Hudson, Principal Engineer, Office of the CTO, Brocade, also identified that the future of optical routing will be based on “routing by reality and programmatic networking through virtualization” [115], giving more control to the data center manager based on the current state of affairs.

The “routing by reality” allow networks to direct traffic based on real-time energy awareness, power minimization, PUE optimization, security protocols, tiered level of redundancy, and per-user allocation. Additionally, there is continued development to utilize biologically-inspired engineering. In the case of optical networks, a new type of data center is emerging based on a 100% optical network with a Jellyfish hierarchy utilizing “a high-capacity of network connections by adopting random graph topology” [116] as well as new developments in Mesh Fabric designs [117], creating a spider web of connections.

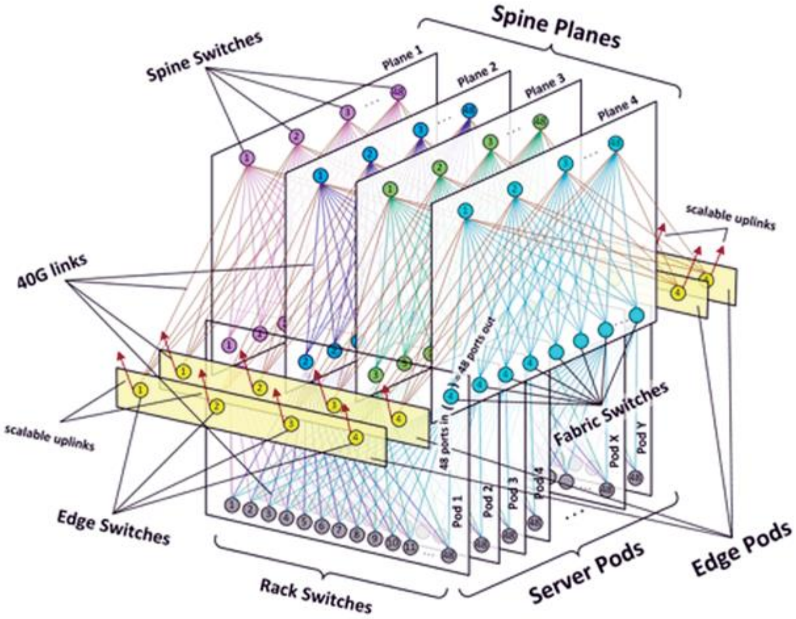


Figure 4.1: Data Center Mesh Fabric
Source: [117]

Insights: Data centers will get smaller, faster, and more portable. We already observe this trend in motion with HP modular POD [118] and Cluster Engineering "Orange Box" [119], which aims to bring the data center down to the size of a suitcase. The other aspect we observe is that data centers may even become a commodity utility service, bundled with our utility bill, and providing key infrastructure services for data storage and communication provided by the local Telco. These two insights point to a possible future whereby we see micro data centers located on a utility grid and providing commoditized services to regional territories. A second insight shows us that the future will see all-optical networks that operate in virtualized environments and relying on software to provide optimized services: the days of using copper are fleeting.

Recommendations: Investing in software-defined optical networks is going to yield a more efficient and controllable data center network than currently available. The benefit of moving to software-define networks will be augmented by the ability to perform robust data analysis and the ability to develop automated algorithms that can optimize various functions in real-time on complex Jellyfish and Mesh Fabric networks.

4.7 Summary of Contributions

This work has provided seven main contributions:

1) A literature review and synthesis of seven subject domains into one integrated framework, as defined in Section 1.7:
    a. Data center market analysis;
    b. Theory on fiber-optic technology;
    c. Internal data center infrastructure;
    d. Systems analysis methods;
    e. Multi-objective system design optimization with genetic algorithms;
    f. Parallel computing with CPU and GPU using vectorization; and
    g. Software development in MATLAB.

2) Experiments, results, and analysis on comparing OM3 and OM4 multi-mode optical fiber at 10G, 40G, and 100G bandwidth, with simulated parallel optics, which is presented in Section 2.2.5. This work yields six equations (Table 2.5 and Table 2.6 above) for modeling: Q-factor versus distance.

3) Experiments, results, and analysis on CPU and GPU performance, with and without vectorization, presented in Section 2.6. This work presents the approaches that significantly reduce cputime for computation by up to 65% (Table 2.15 above).

4) MATLAB based software to facilitate simulation of data center costs and Pareto frontier analysis, which is presented in Section 0 and Section 5.1. This work provides the approach and programming code (Appendix 5.1) for execution of theory into a software-based tool. The software tool performs data center life-cycle cost modeling and yields 3-Dimensional Pareto front visualization of Q-factor versus Capacity vs Life-Cycle Cost, with bi-objective visualizations with color and shape coded Pareto front markers to identify the corresponding solutions.

5) Four theoretical case study's that apply the integrated framework to present Pareto optimal solutions aimed at facilitating augmented decision-making with data center and optical network design, which is presented in Sections 3.6 - 3.9 above. This work demonstrates the application of the theories to simulate multi-objective optimization by simultaneously minimizing life-cycle costs, maximizing capacity of users, and maximizing optical transmission quality (Q-factor).

6) Sensitive analysis on parameters of power costs, PUE, user bandwidth, and genetic algorithm Population Sizes and Maximum Generations, which is presented in Section 3.10 above. This work demonstrates that data centers are most sensitive to the power costs, and, that computational time is most sensitive to the genetic algorithm Population Size. Furthermore, we demonstrate a forecasting method for predicating when power cost will break-even with cabinet server saturation costs. Lastly, we show that when concerned with Q-factor and large capacity needs, the 100G OM4 is the 'alpha-male' solution (i.e., the most dominant non-dominated solution), and for low costs and low-user capacity needs the 10G OM4 is ideal.

7) This work concludes with a summary of the findings, insights, and recommendations for the future, which is presented in Section 4:
    a. A data strategy that seeks out and establishes stable and low cost rates for power will have the most benefit towards data center life-cycle cost reduction;
    b. Calibrating the facility temperature to operate as close as possible to the maximum equipment temperature specifications will have long-term benefit to minimizing costs;
    c. Software-defined parallel-optical networks may yield a more controllable data center network. The benefit of shifting to software-define networks will be augmented by the ability to perform robust data analysis and develop automated algorithms that can optimize various functions in real-time on sophisticated network topologies;
    d. Within the data center, for long reach and low user capacity needs, the 10G OM4 is Pareto optimal and at short reach and high user capacity needs the 100G OM4 is optimal. The 100G OM4 is shown to be the 'alpha-male' of the current technology;
    e. Gaining quantitatively driven insight into the utilization of a data center and optical network helps managers. Vendors need to augment access to data analytics; and
    f. Employment in data centers is growing. The future-of-work will require expertise with systems design, programming, multi-disciplinary optimization, and data visualization.

4.8 Future Work

The scope of this work is rooted in the integration and implementation of theory into a new software tool. Future research can expand the framework into a real-world environment that supports 10G, 40G, 100G, 400G+ networks. Furthermore, the research can also consider building in options to evaluate single-mode fiber to evaluate long reach communication between data centers across geographic distances. Lastly, other evolutionary methods, such as Ant Colony, Tabu Search, Particle Swarm, and Simulated Annealing can be explored to see if these methods provide new insights to solving problems in this field of study.

5 Appendix

5.1 MATLAB code

5.1.1 function Optimize_Callback

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%R.Polany, MIT System Design and Management, Thesis, 2016.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% --- Executes on button press in Optimize.
function Optimize_Callback(hObject, eventdata, handles)
% hObject    handle to Optimize (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
clc;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FACILITY

% Power Cost per kwh
% Variable: PowerCost_kwh
val_PowerCost_kwh = get(handles.PowerCost_kwh,'Value');
if val_PowerCost_kwh == 1;
   values.PowerCost_kwh = .04;
elseif val_PowerCost_kwh == 2;
   values.PowerCost_kwh = .05;
elseif val_PowerCost_kwh == 3;
   values.PowerCost_kwh = .06;
elseif val_PowerCost_kwh == 4;
   values.PowerCost_kwh = .07;
elseif val_PowerCost_kwh == 5;
   values.PowerCost_kwh = .08;
end
PowerCost_kwh = values.PowerCost_kwh;
assignin('base','PowerCost_kwh',PowerCost_kwh);

%Facility Cost
% Variable: Cost_of_Facility
val_Cost_of_Facility = get(handles.Cost_of_Facility,'Value');
if val_Cost_of_Facility == 1;
   values.Cost_of_Facility = 05*10^6;
elseif val_Cost_of_Facility == 2;
   values.Cost_of_Facility = 10*10^6;
elseif val_Cost_of_Facility == 3;
   values.Cost_of_Facility = 20*10^6;
elseif val_Cost_of_Facility == 4;
  values.Cost_of_Facility = 30*10^6;
elseif val_Cost_of_Facility == 5;
  values.Cost_of_Facility = 40*10^6;
elseif val_Cost_of_Facility == 6;
  values.Cost_of_Facility = 50*10^6;
end
Cost_of_Facility=values.Cost_of_Facility;
assignin('base','Cost_of_Facility',Cost_of_Facility);
```

```
%Critical Load
% Variable: MegaWatts_Critical_Load
val_critical_load = get(handles.critical_load,'Value');
if val_critical_load == 1;
  values.critical_load = 05*10^6;
elseif val_critical_load == 2;
  values.critical_load = 10*10^6;
elseif val_critical_load == 3;
  values.critical_load = 15*10^6;
elseif val_critical_load == 4;
  values.critical_load = 20*10^6;
end;
Mega_WattsCritical_Load = values.critical_load;
assignin('base','MegaWatts_Critical_Load',Mega_WattsCritical_Load);

% Average Power Usage
% Variable: Average_Power_Usage
val_avg_power_usage = get(handles.avg_power_usage,'Value');
if val_avg_power_usage == 1;
  values.avg_power_usage= 0.0;
elseif val_avg_power_usage == 2;
  values.avg_power_usage= 0.2;
elseif val_avg_power_usage== 3;
  values.avg_power_usage= 0.4;
elseif val_avg_power_usage == 4;
  values.avg_power_usage= .6;
elseif val_avg_power_usage == 5;
  values.avg_power_usage= .8;
elseif val_avg_power_usage == 6;
  values.avg_power_usage= 1.0;
end;
Average_Power_Usage=values.avg_power_usage;
assignin('base','Average_Power_Usage',Average_Power_Usage);

% Power Utilization Effectiveness
% Variable: PUE
val_PUE = get(handles.PUE,'Value');
if val_PUE == 1;
  values.pue = 1.0;
elseif val_PUE == 2;
  values.pue  = 1.2;
elseif val_PUE == 3;
  values.pue = 1.4;
elseif val_PUE == 4;
  values.pue = 1.5;
elseif val_PUE == 5;
  values.pue = 1.6;
elseif val_PUE == 6;
  values.pue = 1.8;
elseif val_PUE == 7;
  values.pue = 2.0;
end;
PUE=values.pue;
assignin('base','PUE',PUE);

% Power and Cooling Infrastructure (%)
% Variable: Power_Cooling_Infrastructure
```

```
val_Power_Cooling_Infrastructure_Percentage = ....
    get(handles.Power_Cooling_Infrastructure_Percentage,'Value');
if val_Power_Cooling_Infrastructure_Percentage == 1;
  values.p_c_infra = 0.0;
elseif val_Power_Cooling_Infrastructure_Percentage == 2;
  values.p_c_infra = 0.2;
elseif val_Power_Cooling_Infrastructure_Percentage == 3;
  values.p_c_infra = 0.4;
elseif val_Power_Cooling_Infrastructure_Percentage == 4;
  values.p_c_infra = 0.6;
elseif val_Power_Cooling_Infrastructure_Percentage == 5;
  values.p_c_infra = 0.82;
elseif val_Power_Cooling_Infrastructure_Percentage == 6;
  values.p_c_infra = 1.0;
end;
Power_Cooling_Infrastructure_Percentage = values.p_c_infra ;
assignin('base','Power_Cooling_Infrastructure_Percentage',...
    Power_Cooling_Infrastructure_Percentage);

% Facility Amortization (years) --> divide by 12 to get monthly
% Variable: Facility_Amortize_Periods
val_popupmenu38 = get(handles.popupmenu38,'Value');
if val_popupmenu38 == 1;
  values.fac_amortize = 15;
elseif val_popupmenu38 == 2;
  values.fac_amortize = 20;
elseif val_popupmenu38== 3;
  values.fac_amortize = 25;
end;
Facility_Amortize_Periods =values.fac_amortize;
assignin('base','Facility_Amortize_Periods',Facility_Amortize_Periods);

% Sections
% Variable: Sections
val_sections= get(handles.sections_qty,'Value');
if val_sections == 1;
  values.sections = 1;
elseif val_sections == 2;
  values.sections = 2;
end;
Sections = values.sections;
assignin('base','Sections',Sections);
str_sections= sprintf('%d',round(Sections));

% Rows per Sections
% Variable: Rows_Per_Section
val_rows_section = get(handles.rows_qty,'Value');
if val_rows_section == 1;
  values.rows_section = 1;
elseif val_rows_section == 2;
  values.rows_section = 5;
elseif val_rows_section == 3;
  values.rows_section = 10;
end;
Rows_Per_Section = values.rows_section;
assignin('base','Rows_Per_Section',Rows_Per_Section);
str_rows= sprintf('%d',round(Rows_Per_Section));
```

```
% cabinets_qty per Row
% Variable: Cabinets_Per_Row
val_cabinets = get(handles.cabinets_qty,'Value');
if val_cabinets == 1;
  values.cabinets_row = 1;
elseif val_cabinets  == 2;
  values.cabinets_row  = 5;
elseif val_cabinets == 3;
  values.cabinets_row = 10;
end;
Cabinets_Per_Row = values.cabinets_row;
assignin('base','Cabinets_Per_Row',Cabinets_Per_Row);
str_cabinets= sprintf('%d',round(Cabinets_Per_Row));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% Financial Parameters

% Integration
% Variable: Integration_Cost
val_integration = get(handles.integration,'Value');
if val_integration == 1;
  values.integration = 05*10^6;
elseif val_integration  == 2;
  values.integration  = 10*10^6;
elseif val_integration == 3;
  values.integration = 15*10^6;
elseif val_integration == 4;
  values.integration = 20*10^6;
elseif val_integration == 5;
  values.integration = 25*10^6;
end;
Integration_Cost = values.integration;
assignin('base','Integration_Cost',Integration_Cost);

% Maintenance costs
% Variable: Maintenance_Cost
val_maintenance = get(handles.maintenance,'Value');
if val_maintenance == 1;
  values.maintenance = 05*10^6;
elseif val_maintenance  == 2;
  values.maintenance  = 10*10^6;
elseif val_maintenance == 3;
  values.maintenance = 15*10^6;
elseif val_maintenance == 4;
  values.maintenance = 20*10^6;
elseif val_maintenance == 5;
  values.maintenance = 25*10^6;
end;
Maintenance_Cost = values.maintenance;
assignin('base','Maintenance_Cost',Maintenance_Cost);

% Interest Rate (%)
% Variable: Rate
val_interest_rate = get(handles.interest_rate,'Value');
if val_interest_rate == 1;
```

```
  values.interest_rate = .04;
elseif val_interest_rate  == 2;
  values.interest_rate  = .05;
elseif val_interest_rate  == 3;
  values.interest_rate  = .06;
elseif val_interest_rate == 4;
  values.interest_rate = .07;
elseif val_interest_rate == 5;
  values.interest_rate = .08;
end;
Rate = values.interest_rate;
assignin('base','Rate',Rate);
str_interest_rate= sprintf('%d',round(Rate));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Network
network_010Gbps = get(handles.network_010Gbps,'Value');
assignin('base','network_010Gbps',network_010Gbps);

network_040Gbps = get(handles.network_040Gbps,'Value');
assignin('base','network_040Gbps',network_040Gbps);

network_100Gbps = get(handles.network_100Gbps,'Value');
assignin('base','network_100Gbps',network_100Gbps);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Server Configurations
% server_qty (#)
val_server_qty = get(handles.server_qty,'Value');
if val_server_qty == 1;
  values.server_qty = 5;
elseif val_server_qty  == 2;
  values.server_qty = 10;
elseif val_server_qty == 3;
  values.server_qty = 15;
elseif val_server_qty == 4;
  values.server_qty = 20;
elseif val_server_qty == 5;
  values.server_qty = 25;
elseif val_server_qty == 6;
  values.server_qty = 30;
elseif val_server_qty == 7;
  values.server_qty = 35;
elseif val_server_qty == 8;
  values.server_qty = 40;
end;
% total servers for all cabinets_qty
Num_Servers = values.server_qty.*(Cabinets_Per_Row*...
    Rows_Per_Section*Sections);
assignin('base','Num_Servers',Num_Servers);

% server_avgcost ($)
val_server_avgcost = get(handles.server_avgcost,'Value');
if val_server_avgcost == 1;
  values.server_avgcost = 2000;
elseif val_server_avgcost  == 2;
  values.server_avgcost = 4000;
elseif val_server_avgcost == 3;
```

```
  values.server_avgcost = 6000;
elseif val_server_avgcost == 4;
  values.server_avgcost = 8000;
end;
Cost_Per_Server = values.server_avgcost;
assignin('base','Cost_Per_Server',Cost_Per_Server);

% Server Amortization (Years)
val_server_amortize = get(handles.server_amortize,'Value');
if val_server_amortize == 1;
  values.server_amortize = 1;
elseif val_server_amortize == 2;
  values.server_amortize = 3;
elseif val_server_amortize== 3;
  values.server_amortize = 5;
end;
Server_Amoritze_Periods = values.server_amortize;
assignin('base','Server_Amoritze_Periods',Server_Amoritze_Periods);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Network Configurations

% network_avgcost ($)
val_network_avgcost = get(handles.network_avgcost,'Value');
if val_network_avgcost == 1;
  values.network_avgcost = 2500;
elseif val_network_avgcost  == 2;
  values.network_avgcost = 5000;
elseif val_network_avgcost == 3;
  values.network_avgcost = 7500;
elseif val_network_avgcost == 4;
  values.network_avgcost = 10000;
end;
network_avgcost = values.network_avgcost;
assignin('base','network_avgcost',network_avgcost);

% network Amortization (years)
val_network_amortize = get(handles.network_amortize,'Value');
if val_network_amortize == 1;
  values.network_amortize = 1;
elseif val_network_amortize == 2;
  values.network_amortize = 2;
elseif val_network_amortize== 3;
  values.network_amortize = 3;
end;
network_amortize = values.network_amortize;
assignin('base','network_amortize',network_amortize);

%NETWORK
% This project currently utilizes these checkbox for display only.
% The code considers all three modes. A future development could
% allow for individual for analysis.
network_010Gbps = get(handles.network_010Gbps,'Value');
assignin('base','network_010Gbps',network_010Gbps);

network_040Gbps = get(handles.network_040Gbps,'Value');
assignin('base','network_040Gbps',network_040Gbps);
```

```
network_100Gbps = get(handles.network_100Gbps,'Value');
assignin('base','network_100Gbps',network_100Gbps);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Data Configurations

% bandwidth_per_user
val_bandwidth_per_user = get(handles.bandwidth_per_user,'Value');
if val_bandwidth_per_user == 1;
  values.bandwidth_per_user = 1;
elseif val_bandwidth_per_user == 2;
  values.bandwidth_per_user = 2;
elseif val_bandwidth_per_user == 3;
  values.bandwidth_per_user = 10;
elseif val_bandwidth_per_user == 4;
  values.bandwidth_per_user = 25;
elseif val_bandwidth_per_user == 5;
  values.bandwidth_per_user = 50;
elseif val_bandwidth_per_user == 6;
  values.bandwidth_per_user = 100;
end;
bandwidth_per_user = values.bandwidth_per_user;
assignin('base','bandwidth_per_user',bandwidth_per_user);

% Users Load  -- How many users expected during regular use
val_efficiency = get(handles.efficiency,'Value');
if val_efficiency == 1;
  values.efficiency = .20;
elseif val_efficiency == 2;
  values.efficiency = .40;
elseif val_efficiency == 3;
  values.efficiency = .60;
elseif val_efficiency == 4;
  values.efficiency = .80;
end;
efficiency = values.efficiency;
assignin('base','efficiency',efficiency);

% Price Per Meter for OM3_010G
val_OM3_PricePerMeter_010G = get(handles.OM3_PricePerMeter_010G,'Value');
if val_OM3_PricePerMeter_010G == 1;
  values.OM3_PricePerMeter_010G = 1.00;
elseif val_OM3_PricePerMeter_010G == 2;
  values.OM3_PricePerMeter_010G = 1.25;
elseif val_OM3_PricePerMeter_010G == 3
  values.OM3_PricePerMeter_010G = 1.50;
end;
price_per_meter_010G_OM3 = values.OM3_PricePerMeter_010G;
assignin('base','price_per_meter_010G_OM3',price_per_meter_010G_OM3);
str_price_per_meter_010G_OM3 = sprintf('%d',price_per_meter_010G_OM3);

% Price Per Meter for OM3_040G
val_OM3_PricePerMeter_040G = get(handles.OM3_PricePerMeter_040G,'Value');
if val_OM3_PricePerMeter_040G == 1;
  values.OM3_PricePerMeter_040G = 2.00;
elseif val_OM3_PricePerMeter_040G == 2;
  values.OM3_PricePerMeter_040G = 2.25;
```

```
elseif val_OM3_PricePerMeter_040G == 3
  values.OM3_PricePerMeter_040G = 2.50;
end;
price_per_meter_040G_OM3 = values.OM3_PricePerMeter_040G;
assignin('base','price_per_meter_040G_OM3',price_per_meter_040G_OM3);
str_price_per_meter_040G_OM3 = sprintf('%d',price_per_meter_040G_OM3);

% Price Per Meter for OM3_100G
val_OM3_PricePerMeter_100G = get(handles.OM3_PricePerMeter_100G,'Value');
if val_OM3_PricePerMeter_100G == 1;
  values.OM3_PricePerMeter_100G = 1.00;
elseif val_OM3_PricePerMeter_100G == 2;
  values.OM3_PricePerMeter_100G = 2.50;
elseif val_OM3_PricePerMeter_100G == 3
  values.OM3_PricePerMeter_100G = 3.50;
end;
price_per_meter_100G_OM3 = values.OM3_PricePerMeter_100G;
assignin('base','price_per_meter_100G_OM3',price_per_meter_100G_OM3);
str_price_per_meter_100G_OM3 = sprintf('%d',price_per_meter_100G_OM3);

% Price Per Meter for OM4_10G
val_OM4_PricePerMeter_010G = get(handles.OM4_PricePerMeter_010G,'Value');
if val_OM4_PricePerMeter_010G == 1;
  values.OM4_PricePerMeter_010G = 2.00;
elseif val_OM4_PricePerMeter_010G == 2;
  values.OM4_PricePerMeter_010G = 4.50;
elseif val_OM4_PricePerMeter_010G == 3
  values.OM4_PricePerMeter_010G = 6.25;
end;
price_per_meter_010G_OM4 = values.OM4_PricePerMeter_010G;
assignin('base','price_per_meter_010G_OM4',price_per_meter_010G_OM4);
str_price_per_meter_010G_OM4 = sprintf('%d',price_per_meter_010G_OM4);

% Price Per Meter for OM4_40G
val_OM4_PricePerMeter_040G = get(handles.OM4_PricePerMeter_040G,'Value');
if val_OM4_PricePerMeter_040G == 1;
  values.OM4_PricePerMeter_040G = 2.00;
elseif val_OM4_PricePerMeter_040G == 2;
  values.OM4_PricePerMeter_040G = 4.50;
elseif val_OM4_PricePerMeter_040G == 3
  values.OM4_PricePerMeter_040G = 6.25;
end;
price_per_meter_040G_OM4 = values.OM4_PricePerMeter_040G;
assignin('base','price_per_meter_040G_OM4',price_per_meter_040G_OM4);
str_price_per_meter_040G_OM4 = sprintf('%d',price_per_meter_040G_OM4);

% Price Per Meter for OM4_10G
val_OM4_PricePerMeter_100G = get(handles.OM4_PricePerMeter_100G,'Value');
if val_OM4_PricePerMeter_100G == 1;
  values.OM4_PricePerMeter_100G = 2.00;
elseif val_OM4_PricePerMeter_100G == 2;
  values.OM4_PricePerMeter_100G = 4.50;
elseif val_OM4_PricePerMeter_100G == 3
  values.OM4_PricePerMeter_100G = 6.25;
end;
price_per_meter_100G_OM4 = values.OM4_PricePerMeter_100G;
assignin('base','price_per_meter_100G_OM4',price_per_meter_100G_OM4);
```

```
str_price_per_meter_100G_OM4 = sprintf('%d',price_per_meter_100G_OM4);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% Genetic Algorithm Parameters

val_gaparam_popsize = get(handles.gaparam_popsize,'Value');
if val_gaparam_popsize == 1;
  values.gaparam_popsize = 50;
elseif val_gaparam_popsize == 2;
  values.gaparam_popsize = 100;
elseif val_gaparam_popsize == 3;
  values.gaparam_popsize = 150;
elseif val_gaparam_popsize == 4;
  values.gaparam_popsize = 200;
end;
gaparam_popsize = values.gaparam_popsize;
assignin('base','gaparam_popsize',gaparam_popsize);

% gaparam_max_gen defines the maximum generations for the GA algorithm
val_gaparam_max_gen = get(handles.gaparam_max_gen,'Value');
if val_gaparam_max_gen == 1;
  values.gaparam_max_gen = 100;
elseif val_gaparam_max_gen == 2;
  values.gaparam_max_gen = 150;
elseif val_gaparam_max_gen == 3;
  values.gaparam_max_gen = 200;
elseif val_gaparam_max_gen == 4;
  values.gaparam_max_gen = 250;
end;
gaparam_max_gen = values.gaparam_max_gen;
assignin('base','gaparam_max_gen',gaparam_max_gen);

% gaparam_max_gen defines the maximum generations for the GA algorithm
val_gaparam_stall_gen = get(handles.gaparam_stall_gen,'Value');
if val_gaparam_stall_gen == 1;
  values.gaparam_stall_gen = 100;
elseif val_gaparam_stall_gen == 2;
  values.gaparam_stall_gen = 150;
elseif val_gaparam_stall_gen == 3;
  values.gaparam_stall_gen = 200;
elseif val_gaparam_stall_gen == 4;
  values.gaparam_stall_gen = 250;
end;
gaparam_stall_gen = values.gaparam_stall_gen;
assignin('base','gaparam_stall_gen',gaparam_stall_gen);

% gaparam_prob_crossoverfraction (%)
val_gaparam_prob_crossoverfraction = get...
    (handles.gaparam_prob_crossoverfraction,'Value');
if val_gaparam_prob_crossoverfraction == 1;
  values.gaparam_prob_crossoverfraction = .6;
elseif val_gaparam_prob_crossoverfraction == 2;
  values.gaparam_prob_crossoverfraction = 0.7;
elseif val_gaparam_prob_crossoverfraction == 3;
  values.gaparam_prob_crossoverfraction = 0.8;
end;
gaparam_prob_crossoverfraction = values.gaparam_prob_crossoverfraction;
```

```
assignin('base','gaparam_prob_crossoverfraction',...
    gaparam_prob_crossoverfraction);

% gaparam_prob_paretofraction (%)
val_gaparam_prob_paretofraction = ...
    get(handles.gaparam_prob_paretofraction,'Value');
if val_gaparam_prob_paretofraction == 1;
  values.gaparam_prob_paretofraction = .60;
elseif val_gaparam_prob_paretofraction == 2;
  values.gaparam_prob_paretofraction = .70;
elseif val_gaparam_prob_paretofraction == 3;
  values.gaparam_prob_paretofraction = .80;
end;
gaparam_prob_paretofraction = values.gaparam_prob_paretofraction;
assignin('base','gaparam_prob_paretofraction',gaparam_prob_paretofraction);
%% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% COMPUTE THE DATA CENTER
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%DATA CENTER COSTS%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Equations sourced from: James Hamilton
% http://perspectives.mvdirona.com/2008/11...
%           /cost-of-power-in-large-scale-data-centers/
% ***************************************************************
% Infrastructure
% [=-PMT(CostOfMoney/12,FacilityAmortization,FacilityCost,0)]
% Add the Project Integraton Costs and Maintenance Costs
Infrastructure = payper(Rate./12, Facility_Amortize_Periods.*12,...
    (Cost_of_Facility + Integration_Cost + Maintenance_Cost),0,0);
str_Infrastructure= sprintf('%d',round(Infrastructure));
str_Infrastructure = fliplr(regexprep(fliplr(str_Infrastructure),...
    '(\d+\.)?(\d{3})(?=\S+)', '$1$2,'));

% Servers
% [=-PMT(CostOfMoney/12, ServerAmortization, ServerCount*ServerCost, 0)]
Servers = payper(Rate/12, Server_Amoritze_Periods.*12,...
    Num_Servers.*Cost_Per_Server, 0,0);
str_Servers= sprintf('%d',round(Servers));
str_Servers = fliplr(regexprep(fliplr(str_Servers),...
    '(\d+\.)?(\d{3})(?=\S+)', '$1$2,'));

% TOR Switches Networking
% [=-PMT(CostOfMoney/12, TORSwitchAmortization,...
%TORSwitchCount*TORSwitchCost, 0)]
Num_TOR_Switches = (Sections.*Rows_Per_Section.*...
    Cabinets_Per_Row).*2; % two at top of each cabinet
TOR_Switches = payper(Rate./12, network_amortize.*12, ...
    Num_TOR_Switches.*network_avgcost, 0,0);
str_TOR_Switches = sprintf('%d',round(TOR_Switches));
str_TOR_Switches = fliplr(regexprep(fliplr(str_TOR_Switches),...
    '(\d+\.)?(\d{3})(?=\S+)', '$1$2,'));

% Power & Cooling Infrastructure
% [=InfrastructureMonthly*PowerAndCoolikngInfrastructurePercentage]
Power_Cooling_Infrastructure= (Infrastructure.*...
    Power_Cooling_Infrastructure_Percentage);
```

```
str_Power_Cooling_Infrastructure= sprintf('%d',...
    round(Power_Cooling_Infrastructure));
str_Power_Cooling_Infrastructure = ...
    fliplr(regexprep(fliplr(str_Power_Cooling_Infrastructure),...
    '(\d+\.)?(\d{3})(?=\S+)', '$1$2,'));

% Power
% [=MegaWattsCriticalLoad*AveragePowerUsage/1000*PUE*PowerCost*24*365/12]
Power= Mega_WattsCritical_Load*Average_Power_Usage/1000*PUE*...
    PowerCost_kwh*24*(365/12);
str_Power= sprintf('%d',round(Power));
str_Power = fliplr(regexprep(fliplr(str_Power), ...
    '(\d+\.)?(\d{3})(?=\S+)', '$1$2,'));

% Other Infrastructure
% [=+InfrastructureMonthly-PowerAndCoolingInfrastructureMonthly]
Other_Infrastructure= Infrastructure-Power_Cooling_Infrastructure;
str_Other_Infrastructure= sprintf('%d',round(Other_Infrastructure));
str_Other_Infrastructure = fliplr(regexprep(fliplr...
    (str_Other_Infrastructure), '(\d+\.)?(\d{3})(?=\S+)', '$1$2,'));

% Full burdened Power
% [=+PowerAndCoingInfrastructureMonthly+PowerMonthly]
Full_Burdened_Power = Power_Cooling_Infrastructure + Power;
str_Full_Burdened_Power= sprintf('%d',round(Full_Burdened_Power));
str_Full_Burdened_Power = fliplr(regexprep(fliplr...
    (str_Full_Burdened_Power), '(\d+\.)?(\d{3})(?=\S+)', '$1$2,'));
assignin('base','Full_Burdened_Power',Full_Burdened_Power);

% Total
Total_Cost =  Infrastructure + Servers + TOR_Switches + Power;
str_Total= sprintf('%d',round(Total_Cost));
str_Total = fliplr(regexprep(fliplr(str_Total),...
    '(\d+\.)?(\d{3})(?=\S+)', '$1$2,'));


assignin('base','Servers',Servers);
assignin('base','TOR_Switches',TOR_Switches);
assignin('base','Power_Cooling_Infrastructure',...
    Power_Cooling_Infrastructure);
assignin('base','Power',Power);
assignin('base','Other_Infrastructure',Other_Infrastructure);
X = [Servers;TOR_Switches;Power_Cooling_Infrastructure;...
    Power;Other_Infrastructure];
assignin('base','X',X);
%% %% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% % RUN THE GA CODE HERE %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%
% Problem setup
numberOfVariables = 6;   % Number of decision variables

% Bound Constraints
lb = [1, 1, 1, 1, 1, 1];        % Lower bound
ub = [300, 100, 100, 550, 150, 150];         % Upper bound
Bound = [lb; ub];
VLB=lb;
```

```
VUB=ub;
% i=1;
% j=1;
% k=1;

%%Solve the problem without integer constraints
options = gaoptimset('PopulationSize',gaparam_popsize,...
    'CreationFcn', @int_pop,...
    'MutationFcn', @int_mutation,...
    'CrossoverFcn', @int_crossoverarithmetic,...
    'StallGenLimit', gaparam_stall_gen,...
    'Generations', gaparam_max_gen,...
    'PopInitRange', Bound,...
    'Display','none',...
    'ParetoFraction',gaparam_prob_paretofraction,...
    'CrossoverFraction',gaparam_prob_crossoverfraction);

%%%%% DEFINE PARAMETERS%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
sections = Sections; %% GUI INPUT
rows = Rows_Per_Section; %% GUI INPUT
cabs_per_row = Cabinets_Per_Row; %% GUI INPUT
user_Mbps = bandwidth_per_user;  %% GUI INPUT
servers_per_cabinet = values.server_qty; %% GUI INPUT
TOR_switch_cost = payper(Rate./12,network_amortize.*12,...
    network_avgcost,0,0); %% GUI INPUT
users_bw = bandwidth_per_user;  % measure of MBps  %% GUI INPUT
efficiency = efficiency; % efficiency of load relative to max capacity.
distance_from_core = 10;
horizontal = 4 ;
cabinet_width = 4;
vertical = 3;
aisle_width = 5;
%%%%%%%%%
max_distance_010G_OM3 = 330;    % meters as defined per Corning
max_distance_040G_OM3 = 100;    % meters as defined per Corning
max_distance_100G_OM3 = 100;    % meters as defined per Corning
max_distance_010G_OM4 = 550;    % meters as defined per Corning
max_distance_040G_OM4 = 150;    % meters as defined per Corning
max_distance_100G_OM4 = 150;    % meters as defined per Corning
%%%%%%%%%
gigabit2bit = 10^9;         % 1 giga(bit) to bits
speed_010G_OM3_Bits = 10*gigabit2bit;
speed_040G_OM3_Bits = 40*gigabit2bit;
speed_100G_OM3_Bits = 100*gigabit2bit;
speed_010G_OM4_Bits = 10*gigabit2bit;
speed_040G_OM4_Bits = 40*gigabit2bit;
speed_100G_OM4_Bits = 100*gigabit2bit;
%%%%%%%%%
intercabinet_distance = 2;  % assume 2 meters of fiber inside the cabinets
ports_per_server = 2;       % assume 2 ports per server
TOR_per_cabinet = 2;        % assume 2 TOR switches at Top of Rack (TOR)
%%%%%%%%%%%END PARAMETERS DEFINITION%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Define the functions for LifeCycle Costs, Capacity and QFactor
funLCC = @(x)compute_Fitness_v44_LCC(x,sections,rows,...
    cabs_per_row,Full_Burdened_Power,price_per_meter_010G_OM3,...
    price_per_meter_040G_OM3,price_per_meter_100G_OM3,...
```

```
    price_per_meter_010G_OM4,price_per_meter_040G_OM4,...
    price_per_meter_100G_OM4,servers_per_cabinet,...
    Cost_Per_Server, ports_per_server,intercabinet_distance,...
    TOR_per_cabinet,TOR_switch_cost)

funCapacity = @(x)compute_Fitness_v44_Capacity(x,...
    efficiency,max_distance_010G_OM3,max_distance_040G_OM3,...
    max_distance_100G_OM3,max_distance_010G_OM4,max_distance_040G_OM4,...
    max_distance_100G_OM4,users_bw);

funQfactor = @(x)compute_Fitness_v44_Qfactor(x);
%% Run the MOGA
tic;

fprintf('Processing...\n');
[x1,fval1] = gamultiobj(funLCC,...
     numberOfVariables, [], [], [], [], lb, ub, options);

fprintf('Processing...\n');
[x2,fval2] = gamultiobj(funCapacity,...
     numberOfVariables, [], [], [], [], lb, ub, options);

fprintf('Processing...\n');
[x3,fval3] = gamultiobj(funQfactor,...
     numberOfVariables, [], [], [], [], lb, ub, options);
 %%

%Process to ensure FVALS are the same size.
 while size(fval1(:),1 )~= size(fval2(:),1) || size(fval1(:),1)...
         ~= size(fval3(:),1) || size(fval2(:),1) ~= size(fval3(:),1);

     fprintf('Processing...\n');
[x1,fval1] = gamultiobj(funLCC,...
     numberOfVariables, [], [], [], [], lb, ub, options);

 fprintf('Processing...\n');
[x2,fval2] = gamultiobj(funCapacity,...
     numberOfVariables, [], [], [], [], lb, ub, options);

 fprintf('Processing...\n');
[x3,fval3] = gamultiobj(funQfactor,...
     numberOfVariables, [], [], [], [], lb, ub, options);
 end
%
%% Setup the Pareto Matrix
OM3_10G =  [fval1(:,1) -fval2(:,1) -fval3(:,1)];
OM3_40G =  [fval1(:,2) -fval2(:,2) -fval3(:,2)];
OM3_100G = [fval1(:,3) -fval2(:,3) -fval3(:,3)];
OM4_10G =  [fval1(:,4) -fval2(:,4) -fval3(:,4)];
OM4_40G =  [fval1(:,5) -fval2(:,5) -fval3(:,5)];
OM4_100G = [fval1(:,6) -fval2(:,6) -fval3(:,6)];
Pareto =   [OM3_10G;OM3_40G;OM3_100G;OM4_10G;OM4_40G;OM4_100G];
%% Clear and reset the axes
handles.axes32 = gca;  % essential to remind otherwise lost with subplots.
%http://www.mathworks.com/matlabcentral/answers/...
%   48256-axes-problem-in-matlab-gui
```

```
cla(handles.axes32,'reset');
axes(handles.axes32);
%% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% %Plot B: Cost vs Distance
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
h233 = subplot(2,3,3);
cla(h233,'reset');
subplot(2,3,3);
p = get(h233,'position');
p(1) = p(1)*1.02; % Add 0 percent to x
p(2) = p(2)*1.0; % Add 0 percent to y
p(3) = p(3)*1.35; % Add 20 percent to width
p(4) = p(4)*1.10; % Add 10 percent to height
set(h233, 'position', p);

% Cost vs Distance
fval1Pareto(:,1)= [x1(:,1);x1(:,2);x1(:,3);x1(:,4);x1(:,5);x1(:,6)];
fval1Pareto(:,2)= -[fval1(:,1);fval1(:,2);fval1(:,3);fval1(:,4);...
    fval1(:,5);fval1(:,6)];

Pareto_x1_vs_fval1 = zeros(size(fval1Pareto,1),2);
Pareto_x1_vs_fval1_sorted= zeros(size(fval1Pareto,1),2);
a=zeros(size(fval1Pareto,1),2);
x=zeros(size(fval1Pareto,1),1);
y=zeros(size(fval1Pareto,1),1);
Pareto_x1_vs_fval1 = [fval1Pareto(:,1) fval1Pareto(:,2)];
Pareto_x1_vs_fval1_sorted = sortrows(Pareto_x1_vs_fval1,2);
a=Pareto_x1_vs_fval1_sorted  ;
x= fval1Pareto(:,1);
y= fval1Pareto(:,2);
N = size(Pareto_x1_vs_fval1_sorted,1);
compare_matrix= gpuArray(size(N,N));                            % GPU array
compare_matrix = cell2mat(arrayfun(@(ii) all(bsxfun(@(x,y)...   % RUN GPU
    x<=min(y),a,a(ii,:)),2),1:N,'uni',false));                  % RUN GPU
compare_matrix(1:N+1:N^2)=false; % set diagonal to false
dominated_idxs = size(size(fval1Pareto,1),1);
dominated_idxs = any(compare_matrix,2);
a(dominated_idxs ,:) = [];

hold on;
plot(a(:,1),-a(:,2),...
    'MarkerFaceColor',[1 1 1],'MarkerEdgeColor',[0 .8 0],...
    'MarkerSize',10,...
    'Marker','square',...
    'LineWidth',1,...
    'Color',[1 0 0]);
set(gca,'XScale','log');


ParetoLCC_X = a(:,1);
ParetoLCC_Y = -a(:,2);

hold on;
scatter(x1(:,1),fval1(:,1),'ok','Display','10G OM3',...
    'MarkerEdgeColor',[0 0 0]);  %black
scatter(x1(:,2),fval1(:,2),'ob','Display','40G OM3',...
    'MarkerEdgeColor',[0 0 1]); %blue
```

```
scatter(x1(:,3),fval1(:,3),'om','Display','100G OM3',...
    'MarkerEdgeColor',[1 0 1]); %magenta
scatter(x1(:,4),fval1(:,4),'Xk','Display','10G OM4',...
    'MarkerEdgeColor',[0 0 0]);  %black
scatter(x1(:,5),fval1(:,5),'Xb','Display','40G OM4',...
    'MarkerEdgeColor',[0 0 1]); %blue
scatter(x1(:,6),fval1(:,6),'Xm','Display','100G OM4',...
    'MarkerEdgeColor',[1 0 1]); %magenta


title({'Cost ($) vs Distance(m)'},'Color','blue');
xlabel({'Distance (m)'});
ylabel({'Cost ($)'});
text(-.11,1.04,'(B)','Units', 'Normalized', 'VerticalAlignment',...
    'Bottom','color','k','fontw','b','FontSize',8)

set(gca,'XScale','log');
set(gca,'FontSize',7);
set(gcf,'Color','w');


legendsize= legend('Pareto','OM3 10G','OM3 40G','OM3 100G','OM4 10G',...
    'OM4 40G','OM4 100G', 'Location','northwest');
set(legendsize,'FontSize',7)

grid on;
box on;

%
%% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Plot C: Capacity vs Distance
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

h235 = subplot(2,3,5);
cla(h235,'reset');
subplot(2,3,5);

p = get(h235,'position');
p(1) = p(1)*(.85);   % Substract 15% to x
p(2) = p(2)*.7;     % Substract 30% to y
p(3) = p(3)*1.4;     % Add 40% to width
p(4) = p(4)*1.1;    % Add 10% to height
set(h235, 'position', p);

% Capacity vs Distance
fval2Pareto(:,1)= [x2(:,1);x2(:,2);x2(:,3);x2(:,4);x2(:,5);x2(:,6)];
fval2Pareto(:,2)= [fval2(:,1);fval2(:,2);fval2(:,3);fval2(:,4);...
    fval2(:,5);fval2(:,6)];

Pareto_x2_vs_fval2 = zeros(size(fval2Pareto,1),2);
Pareto_x2_vs_fval2_sorted= zeros(size(fval2Pareto,1),2);
a=zeros(size(fval2Pareto,1),2);
x=zeros(size(fval2Pareto,1),1);
y=zeros(size(fval2Pareto,1),1);
Pareto_x2_vs_fval2 = [fval2Pareto(:,1) -fval2Pareto(:,2)];
Pareto_x2_vs_fval2_sorted = sortrows(Pareto_x2_vs_fval2,1);
a=Pareto_x2_vs_fval2_sorted  ;
```

```
x= fval2Pareto(:,1);
y= -fval2Pareto(:,2);
N = size(Pareto_x2_vs_fval2_sorted,1);
compare_matrix= gpuArray(size(N,N));                             % GPU array
compare_matrix = cell2mat(arrayfun(@(ii) all(bsxfun(@(x,y)...    % RUN GPU
    x<=min(y),a,a(ii,:)),2),1:N,'uni',false));                   % RUN GPU
compare_matrix(1:N+1:N^2)=false; % set diagonal to false
dominated_idxs = size(size(fval2Pareto,1),1);
dominated_idxs = any(compare_matrix,2);
a(dominated_idxs ,:) = [];

hold on;
plot(a(:,1),a(:,2),...
    'MarkerFaceColor',[1 1 1],'MarkerEdgeColor',[0 .8 0],...
    'MarkerSize',10,...
    'Marker','square',...
    'LineWidth',1,...
    'Color',[1 0 0]);

ParetoCapacity_X = a(:,1);
ParetoCapacity_Y = a(:,2);

hold on;
scatter(x2(:,1),-fval2(:,1),'ok','Display','10G OM3',...
    'MarkerEdgeColor',[0 0 0]);%black
scatter(x2(:,2),-fval2(:,2),'ob','Display','40G OM3',...
    'MarkerEdgeColor',[0 0 1]);%blue
scatter(x2(:,3),-fval2(:,3),'om','Display','100G OM3',...
    'MarkerEdgeColor',[1 0 1]); %magenta
scatter(x2(:,4),-fval2(:,4),'Xk','Display','10G OM4',...
    'MarkerEdgeColor',[0 0 0]);%black
scatter(x2(:,5),-fval2(:,5),'Xb','Display','40G OM4',...
    'MarkerEdgeColor',[0 0 1]);%blue
scatter(x2(:,6),-fval2(:,6),'Xm','Display','100G OM4',...
    'MarkerEdgeColor',[1 0 1]); %magenta

title({'Capacity (users) vs. Distance(m)'},'Color','blue');
xlabel({'Distance (m)'});
ylabel({'Capacity (users)'});
text(-.11,1.04,'(C)','Units', 'Normalized', 'VerticalAlignment',...
    'Bottom','color','k','fontw','b','FontSize',8)

set(gca,'XScale','log');
set(gca,'FontSize',7);
set(gcf,'Color','w');
grid on;
box on;
%
%% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Plot D:  Qfactor vs Distance
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
h236 = subplot(2,3,6);
cla(h236);
p = get(h236,'position');
p(1) = p(1)*1.02; % Add 2 percent to x
p(2) = p(2)*.7; % Add -30 percent to y
p(3) = p(3)*1.35; % Add 35 percent to width
```

```
p(4) = p(4)*1.10; % Add 10 percent to height
set(h236, 'position', p);

% Qfactor vs Distance
fval3Pareto(:,1)= [x3(:,1);x3(:,2);x3(:,3);x3(:,4);x3(:,5);x3(:,6)];
fval3Pareto(:,2)= -[fval3(:,1);fval3(:,2);fval3(:,3);fval3(:,4);...
    fval3(:,5);fval3(:,6)];

Pareto_x3_vs_fval3 = zeros(size(fval3Pareto,1),2);
Pareto_x3_vs_fval3_sorted= zeros(size(fval3Pareto,1),2);
a=zeros(size(fval3Pareto,1),2);
x=zeros(size(fval3Pareto,1),1);
y=zeros(size(fval3Pareto,1),1);
Pareto_x3_vs_fval3 = [fval3Pareto(:,1) fval3Pareto(:,2)];
Pareto_x3_vs_fval3_sorted = sortrows(Pareto_x3_vs_fval3,2);
a=Pareto_x3_vs_fval3_sorted  ;
x= fval3Pareto(:,1);
y= fval3Pareto(:,2);
N = size(Pareto_x3_vs_fval3_sorted,1);
compare_matrix= gpuArray(size(N,N));                              % GPU array
compare_matrix = cell2mat(arrayfun(@(ii) all(bsxfun(@(x,y)...    % RUN GPU
    x<=min(y),a,a(ii,:)),2),1:N,'uni',false));                    % RUN GPU
compare_matrix(1:N+1:N^2)=false; % set diagonal to false
dominated_idxs = size(size(fval3Pareto,1),1);
dominated_idxs = any(compare_matrix,2);
a(dominated_idxs ,:) = [];

hold on;

plot(a(:,1),a(:,2),...
    'MarkerFaceColor',[1 1 1],'MarkerEdgeColor',[0 .8 0],...
    'MarkerSize',10,...
    'Marker','square',...
    'LineWidth',1,...
    'Color',[1 0 0]);

ParetoQfactor_X = a(:,1);
ParetoQfactor_Y = a(:,2);

hold on;
scatter(x3(:,1),-fval3(:,1),'ok','Display','10G OM3',...
    'MarkerEdgeColor',[0 0 0]);
scatter(x3(:,2),-fval3(:,2),'ob','Display','40G OM3',...
    'MarkerEdgeColor',[0 0 1]);
scatter(x3(:,3),-fval3(:,3),'om','Display','100G OM3',...
    'MarkerEdgeColor',[1 0 1]);
scatter(x3(:,4),-fval3(:,4),'Xk','Display','10G OM4',...
    'MarkerEdgeColor',[0 0 0]);
scatter(x3(:,5),-fval3(:,5),'Xb','Display','40G OM4',...
    'MarkerEdgeColor',[0 0 1]);
scatter(x3(:,6),-fval3(:,6),'Xm','Display','100G OM4',...
    'MarkerEdgeColor',[1 0 1]);

title({'Qfactor vs Distance(m)'},'Color','blue');
xlabel({'Distance (m)'});
ylabel({'Qfactor'});
text(-.11,1.04,'(D)','Units', 'Normalized', 'VerticalAlignment',...
```

```
    'Bottom','color','k','fontw','b','FontSize',8)

set(gca,'XScale','log');
set(gca,'FontSize',7);
set(gcf,'Color','w');
grid on;
box on;
%
%% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Plot A:  Pareto Fronter for Qfactor vs Capacity vs Cost
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

h232 = subplot(2,3,2);
cla(h232);
subplot(2,3,2);
p = get(h232,'position');
p(1) = p(1)*(.85);   % Substract 5 percent to x
p(2) = p(2)*1.0;    % Add 0 percent to y
p(3) = p(3)*1.2;     % Add 0 percent to width
p(4) = p(4)*1.1;    % Add 0 percent to height
set(h232, 'position', p);

set(h232,'xlim',[min(+fval1(:)) max(+fval1(:))]);
set(h232,'ylim',[min(-fval2(:)) max(-fval2(:))]);
set(h232,'zlim',[min(-fval3(:)) max(-fval3(:))]);

gvx = ParetoLCC_Y;
gvy = ParetoCapacity_Y;
gvz = ParetoQfactor_Y;

m = size(gvx,1);
n = size(gvy,1);
q = size(gvz,1);
A = [m n q];

scale_gvx = size(gvx,1)/ min(A); %  SCALE FACTOR FOR HORZCAT PURPOSES
scale_gvy = size(gvy,1)/ min(A); %  SCALE FACTOR FOR HORZCAT PURPOSES
scale_gvz = size(gvz,1)/ min(A); %  SCALE FACTOR FOR HORZCAT PURPOSES

gvxA = gvx;
gvyA = gvy;
gvzA = gvz;

gvxA = gvx(1:scale_gvx:end);        %RESCALE THE MATRIX
gvyA = gvy(1:scale_gvy:end);        %RESCALE THE MATRIX
gvzA = gvz(1:scale_gvz:end);        %RESCALE THE MATRIX

hold on
plot3(gvxA,gvyA,gvzA,'-s','Color','red','Display','Pareto')

title({'Pareto: Qfactor vs. Capacity vs. Cost'},'Color','blue');
xlabel({'Cost'},'FontWeight','bold');
ylabel({'Capacity'},'FontWeight','bold');
zlabel({'Qfactor'},'FontWeight','bold');
set(gca,'FontSize',7);
set(gcf,'Color','w');
```

```
 set(gca,'LooseInset',get(gca,'TightInset'))

text(-.11,1.04,'(A)','Units', 'Normalized', 'VerticalAlignment',...
    'Bottom','color','k','fontw','b','FontSize',8)

legend('Pareto');
legendPlotA = legend('Pareto','Location','northeast');
set(legendPlotA,'FontSize',10)

grid on;
box on;
view([120 10]);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%



% PIE CHART %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% in row 1 position 1
h231 = subaxis(2,3,1,'MarginTop',-.01,'MarginBottom',.02,...
    'PaddingBottom',.1,'ML',.1,'MR',.2,'SpacingHoriz',.125,...
    'SpacingVert',.125);
cla(h231);

subaxis(2,3,1,'MarginTop',-.01,'MarginBottom',.02,'PaddingBottom',.1,...
    'ML',.1,'MR',.2,'SpacingHoriz',.125,'SpacingVert',.125);

h = pie(X);
hText = findobj(h,'Type','text'); % text object handles
set(hText(1),'Fontsize',7);
set(hText(2),'Fontsize',7);
set(hText(3),'Fontsize',7);
set(hText(4),'Fontsize',7);
set(hText(5),'Fontsize',7);
percentValues = get(hText,'String'); % percent values
str = {'Servers: ';'Switches: ';'P&C: ';'Power: ';'Other: '}; % strings
combinedstrings = strcat(str,percentValues); % strings and percent values
oldExtents_cell = get(hText,'Extent'); % cell array
oldExtents = cell2mat(oldExtents_cell); % numeric array
hText(1).String = combinedstrings(1);
hText(2).String = combinedstrings(2);
hText(3).String = combinedstrings(3);
hText(4).String = combinedstrings(4);
hText(5).String = combinedstrings(5);
newExtents_cell = get(hText,'Extent'); % cell array
newExtents = cell2mat(newExtents_cell); % numeric array
width_change = newExtents(:,3)-oldExtents(:,3);
signValues = sign(oldExtents(:,1));
offset = signValues.*(width_change/2);
textPositions_cell = get(hText,{'Position'}); % cell array
textPositions = cell2mat(textPositions_cell); % numeric array
textPositions(:,1) = textPositions(:,1) + offset; % add offset
hText(1).Position = textPositions(1,:);
hText(2).Position = textPositions(2,:);
hText(3).Position = textPositions(3,:);
hText(4).Position = textPositions(4,:);
hText(5).Position = textPositions(5,:);
title('Data Center Costs','FontSize',8,'Color','blue','FontWeight','bold')
```

```
%% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%Organize the results to command window
fprintf('******************************\n')
disp(['Total (monthly): $',str_Total])
fprintf('******************************\n')
disp(['Infrastructure $',str_Infrastructure])
disp(['Servers: $',str_Servers])
disp(['Power Cooling_Infrastructure: $',str_Power_Cooling_Infrastructure])
disp(['Power: $',str_Power])
disp(['Other Infrastructure: $',str_Other_Infrastructure])
disp(['Fully Burdened Power: $',str_Full_Burdened_Power])
fprintf('******************************\n')
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%DATA TABLE GUI
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
colnames = {'Parameter','Result'};

%Table Table_GUI

x01={'Total LCC($)[monthly]'};
y01=str_Total;

x02={'Infra.($)'};
y02=str_Infrastructure;

x03={'Servers($)'};
y03=str_Servers;

x04={'Power Cooling($)'};
y04=str_Power;

x05={'Other Infra.($)'};
y05= str_Other_Infrastructure;

x06= {'Burdened Power ($)'};
y06= str_Full_Burdened_Power;

x07 = {'PUE'};
y07 = PUE;

x08 = {'$/kwh'};
y08 = PowerCost_kwh;

x09 = {'Critical Load (MW)'};
y09 = Mega_WattsCritical_Load./10^6;

x10 = {'Amortize (Yrs)'};
y10 = Facility_Amortize_Periods;

x11 = {'----------'};
y11 = {'---'};

x12 = {'Sections'};
y12= str_sections;

x13 = {'Rows'};
y13 = str_rows;
```

```
x14 = {'Cabinet/Row'};
y14 = str_cabinets;

x15 = {'Architecture'};
y15 = 'TOR';
%
x16 = {'----------'};
y16 = {'---'};

cputime = toc;
x17 = {'CPUtime (s)'};
y17 = cputime;

% Build GUI Tables
Data1=[x01,y01;x02,y02;x03,y03;x04,y04;x05,y05;x06,y06;x07,y07;...
    x08,y08;x09,y09;x10,y10;x11,y11;x12,y12;x13,y13;x14,y14;x15,y15;...
    x16,y16;x17,y17];

% Display the results to the GUI table
set(handles.output_table_GUI_01,'data',...
    [x01,y01;x02,y02;x03,y03;x04,y04;...
    x05,y05;x06,y06;x07,y07;x08,y08;x09,y09;x10,y10;...
    x11,y11;x12,y12;x13,y13;x14,y14;x15,y15;x16,y16;...
    x17,y17],'ColumnName',colnames);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

5.1.2 function [LCC] = computeLCC

```
function [J1_LCC] = compute_Fitness_v44_LCC(x,sections,rows,...
    cabs_per_row,Full_Burdened_Power,price_per_meter_010G_OM3,...
    price_per_meter_040G_OM3,price_per_meter_100G_OM3,...
    price_per_meter_010G_OM4,price_per_meter_040G_OM4,...
    price_per_meter_100G_OM4,servers_per_cabinet,...
    Cost_Per_Server, ports_per_server,intercabinet_distance,...
    TOR_per_cabinet,TOR_switch_cost)

x(1) = x(:,1);  % Vectorize using columns
x(2) = x(:,2);  % Vectorize using columns
x(3) = x(:,3);  % Vectorize using columns
x(4) = x(:,4);  % Vectorize using columns
x(5) = x(:,5);  % Vectorize using columns
x(6) = x(:,6);  % Vectorize using columns

AvgPowerPerCabinetCost = Full_Burdened_Power./(sections.*rows.*cabs_per_row);
ServerCosts = servers_per_cabinet.*Cost_Per_Server;
CabinetCableCosts = servers_per_cabinet.*ports_per_server.*...
    intercabinet_distance;

%010G_OM3
J1_LCC(1) = sections.*(...
    x(1).*price_per_meter_010G_OM3.*TOR_per_cabinet + ...
    TOR_per_cabinet.*TOR_switch_cost + ...
    CabinetCableCosts.*price_per_meter_010G_OM3 +...
    ServerCosts + ...
    AvgPowerPerCabinetCost);

%040_OM3
J1_LCC(2) = sections.*(...
    x(2).*price_per_meter_040G_OM3.*TOR_per_cabinet + ...
    TOR_per_cabinet.*TOR_switch_cost + ...
    CabinetCableCosts.*price_per_meter_040G_OM3 +...
    ServerCosts + ...
    AvgPowerPerCabinetCost);

%100G_OM3
J1_LCC(3) = sections.*(...
    x(3).*price_per_meter_100G_OM3.*TOR_per_cabinet + ...
    TOR_per_cabinet.*TOR_switch_cost + ...
    CabinetCableCosts.*price_per_meter_100G_OM3 +...
    ServerCosts + ...
    AvgPowerPerCabinetCost);

%010G_OM4
J1_LCC(4) = sections.*(...
    x(4).*price_per_meter_010G_OM4.*TOR_per_cabinet + ...
    TOR_per_cabinet.*TOR_switch_cost + ...
    CabinetCableCosts.*price_per_meter_010G_OM4 +...
    ServerCosts + ...
    AvgPowerPerCabinetCost);

%040G_OM4
J1_LCC(5) = sections.*(...
```

```
    x(5).*price_per_meter_040G_OM4.*TOR_per_cabinet + ...
    TOR_per_cabinet.*TOR_switch_cost + ...
    CabinetCableCosts.*price_per_meter_040G_OM4 +...
    ServerCosts + ...
    AvgPowerPerCabinetCost);

%100G_OM4
J1_LCC(6) = sections.*(...
    x(6).*price_per_meter_100G_OM4.*TOR_per_cabinet + ...
    TOR_per_cabinet.*TOR_switch_cost + ...
    CabinetCableCosts.*price_per_meter_100G_OM4 +...
    ServerCosts + ...
    AvgPowerPerCabinetCost);
```

5.1.3 function[Capacity] = computeCapacity

```
function [J2_Capacity] = compute_Fitness_v42_Capacity(x,...
    efficiency,max_distance_010G_OM3,max_distance_040G_OM3,...
    max_distance_100G_OM3,max_distance_010G_OM4,max_distance_040G_OM4,...
    max_distance_100G_OM4,users_bw);

x(1) = x(:,1);  % Vectorize using columns
x(2) = x(:,2);  % Vectorize using columns
x(3) = x(:,3);  % Vectorize using columns
x(4) = x(:,4);  % Vectorize using columns
x(5) = x(:,5);  % Vectorize using columns
x(6) = x(:,6);  % Vectorize using columns

% Max capacity of users at network efficiency
users_Gbps = users_bw./10^3;
Max_Capacity_010G_OM3 = (010/users_Gbps).*efficiency;
Max_Capacity_040G_OM3 = (040/users_Gbps).*efficiency;
Max_Capacity_100G_OM3 = (100/users_Gbps).*efficiency;
Max_Capacity_010G_OM4 = (010/users_Gbps).*efficiency;
Max_Capacity_040G_OM4 = (040/users_Gbps).*efficiency;
Max_Capacity_100G_OM4 = (100/users_Gbps).*efficiency;

%OM3 10G
J2_Capacity(1) = -1.*(Max_Capacity_010G_OM3.*(max_distance_010G_OM3-x(1))...
    ./max_distance_010G_OM3);

%OM3 40G
J2_Capacity(2) = -1.*(Max_Capacity_040G_OM3.*(max_distance_040G_OM3-x(2))...
    ./max_distance_040G_OM3);

%OM3 100G
J2_Capacity(3) = -1.*(Max_Capacity_100G_OM3.*(max_distance_100G_OM3-x(3))...
    ./max_distance_100G_OM3);

%OM4 10G
J2_Capacity(4) = -1.*(Max_Capacity_010G_OM4.*(max_distance_010G_OM4-x(4))...
    ./max_distance_010G_OM4);

%OM4 40G
J2_Capacity(5) = -1.*(Max_Capacity_040G_OM4.*(max_distance_040G_OM4-x(5))...
    ./max_distance_040G_OM4);

%OM4 100G
J2_Capacity(6) = -1.*(Max_Capacity_100G_OM4.*(max_distance_100G_OM4-x(6))...
    ./max_distance_100G_OM4);
```

5.1.4 function [Qfactor] = computeQfactor

```
function [J3_Qfactor] = compute_Fitness_v42_Qfactor(x);
x(1) = x(:,1);  % Vectorize using columns
x(2) = x(:,2);  % Vectorize using columns
x(3) = x(:,3);  % Vectorize using columns
x(4) = x(:,4);  % Vectorize using columns
x(5) = x(:,5);  % Vectorize using columns
x(6) = x(:,6);  % Vectorize using columns

%%% OM3, Equations 2.5 - 2.7
% Eqn. 2.5, y =.00000*exp(0.07584*x) + 7.87968*exp(-.0001*x)
% Eqn. 2.6, y = 5.47297*exp(-0.12299*x)+7.27510*exp(-0.0004*x)
% Eqn. 2.7, y = 5.59373292*exp(-0.12927862*x)+7.28378306*exp(-0.00042308*x)
%%%%%%%%%
%OM3 10G
%y = 7.37968.*exp(-.000215) Eqn.(2.5)
J3_Qfactor(1) = -1.*(7.37968.*exp(-.000215*x(1)));

%OM3 40G
%y = 5.47297*exp(-0.12299*x) + 7.27510*exp(-0.0004*x) Eqn. 2.6
J3_Qfactor(2) = -1.*((5.47297.*exp(-0.12299.*x(2))...
    +7.27510.*exp(-0.0004.*x(2))));

%OM3 100G
%y = 5.59373292*exp(-0.12927862*x)+7.28378306*exp(-0.00042308*x) Eqn 2.7
J3_Qfactor(3) = -1.*((5.59373292.*exp(-0.12927862.*x(3)) ...
    + 7.28378306.*exp(-0.00042308.*x(3))));

%%% OM4, Equations 2.8 - 2.9
% Eqn. 2.8, y = 7.77941*exp(-0.00015*x)+-0.000001*exp(0.021*x)
% Eqn. 2.9, y = 5.08844*exp(-0.04094*x)+7.15245*exp(0.00001*x)
% Eqn. 2.10, y = 4.89846*exp(-0.04601*x)+7.22401*exp(0.0001*x)
%%%%%%%%%
%OM4 10G
%y = 7.77941*exp(-0.00015*x)-0.000001*exp(0.021*x) Eqn. 2.8
J3_Qfactor(4) = -1.*(7.77941.*exp(-0.00015.*x(4)) ...
    - 0.000001.*exp(0.021.*x(4)));

%OM4 40G
%y = 5.08844*exp(-0.04094*x) + 7.15245*exp(0.0000004*x) Eqn. 2.9
J3_Qfactor(5) = -1.*(5.08844.*exp(-0.04094.*x(5)) ...
    + 7.15245.*exp(0.0000004.*x(5)));

%OM4 100G
%y = 4.89846*exp(-0.04601*x)+7.22401*exp(-.0000001*x)) Eqn 2.10
J3_Qfactor(6) = -1.*(4.89846.*exp(-0.04601.*x(6)) ...
    + 7.72401.*exp(-0.0000001.*x(6)));
```

5.1.5 function [Population] = int_pop

```
% File reference: exampleIntGAMULTIOBJ.zip
% http://www.mathworks.com/matlabcentral/answers/103369-is-it-possible-to
%           -solve-a-mixed-integer-multi-objective-optimization-...
%           -problem-using-global-optimizati
%
% MATLAB Answers™
% Is it possible to solve a mixed-integer multi-objective optimization ...
%    problem using Global Optimization Toolbox 3.2.4 (R2013b)?
% Asked by MathWorks Support Team on 25 Oct 2013

function Population = int_pop(GenomeLength, ~, options)
% INT_POP Function that creates an initial population satisfying bounds and
% integer constraints

totalPopulation = sum(options.PopulationSize);

%IntCon constraints
IntCon = [1, 2];

range = options.PopInitRange;
lower = range(1,:);
span =  range(2,:) - lower;


Population = repmat(lower,totalPopulation,1 )+  ...
    repmat(span,totalPopulation,1) .* rand(totalPopulation, GenomeLength);

x = rand;
if x>=0.5
    Population(:,IntCon) = floor(Population(:, IntCon));
else
    Population(:,IntCon) = ceil(Population(:, IntCon));
end
Population = checkbounds(Population, range);
```

5.1.6 function [mutationChildren] = int_mutation

```
% File reference: exampleIntGAMULTIOBJ.zip
% http://www.mathworks.com/matlabcentral/answers/103369-is-it-possible-to
%           -solve-a-mixed-integer-multi-objective-optimization-...
%           -problem-using-global-optimizati
%
% MATLAB Answers™
% Is it possible to solve a mixed-integer multi-objective optimization ...
%    problem using Global Optimization Toolbox 3.2.4 (R2013b)?
% Asked by MathWorks Support Team on 25 Oct 2013

function mutationChildren = int_mutation(parents, options, GenomeLength, ...
    ~, state, ~, ~)

% Creates the mutated children using the Gaussian distribution.

%IntCon constraints
IntCon = [1, 2];

shrink = 0.01;
scale = 1;
scale = scale - shrink * scale * state.Generation/options.Generations;
range = options.PopInitRange;
lower = range(1,:);
upper = range(2,:);
scale = scale * (upper - lower);
mutationPop =  length(parents);

mutationChildren =  repmat(lower,mutationPop,1) +  ...
    repmat(scale, mutationPop,1) .* rand(mutationPop, GenomeLength);

x = rand;
if x>=0.5
    mutationChildren(:, IntCon) = floor(mutationChildren(:,IntCon));
else
    mutationChildren(:, IntCon) = ceil(mutationChildren(:,IntCon));
end

mutationChildren = checkbounds(mutationChildren, range);
```

5.1.7 function [xoverKids] = int_crossoverarithemtic

```
% File reference: exampleIntGAMULTIOBJ.zip
% http://www.mathworks.com/matlabcentral/answers/103369-is-it-possible-to
%           -solve-a-mixed-integer-multi-objective-optimization-...
%           -problem-using-global-optimizati
%
% MATLAB Answers™
% Is it possible to solve a mixed-integer multi-objective optimization ...
%    problem using Global Optimization Toolbox 3.2.4 (R2013b)?
% Asked by MathWorks Support Team on 25 Oct 2013


function xoverKids  =
int_crossoverarithmetic(parents,options,GenomeLength,...
    FitnessFcn,unused,thisPopulation)


%IntCon constraints
IntCon = [1, 2];

% How many children to produce?
nKids = length(parents)/2;
% Allocate space for the kids
xoverKids = zeros(nKids,GenomeLength);
% To move through the parents twice as fast as the kids are
% being produced, a separate index for the parents is needed
index = 1;
% for each kid...
for i=1:nKids
    % get parents
    r1 = parents(index);
    index = index + 1;
    r2 = parents(index);
    index = index + 1;
    % Children are arithmetic mean of two parents
    % ROUND will guarantee that they are integer.
    alpha = rand;
    xoverKids(i,:) = alpha*thisPopulation(r1,:) + ...
        (1-alpha)*thisPopulation(r2,:);
end

x = rand;
if x>=0.5
    xoverKids(:, IntCon) = floor(xoverKids(:, IntCon));
else
    xoverKids(:, IntCon) = ceil(xoverKids(:, IntCon));
end
range = options.PopInitRange;
xoverKids = checkbounds(xoverKids, range);
```

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