A Multi-Axis Approach to Complexity Management
by
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ABSTRACT

A high degree of complexity exists in the product, processes, organization and supply chain at HIGHVOLT Prüftechnik GmbH, subsidiary of Maschinenfabrik Reinhausen. The current state complexity results from unique market dynamics, the highly technical nature of the solutions offered and customer demands for vast customization. Paramount strategic goals of the company are to reduce delivery time, decrease cost and mitigate risk. The focus of this project is to achieve these strategic goals through complexity management.

We hypothesize that by beginning at a high-level collection of process, product and organizational complexity information, we can achieve a highly effective method for managing the complexity in the system. This project uses two primary diagnostic analysis techniques: thorough core process flow mapping and pain-point data collection from critical stakeholders. Synthesis of the process flow mapping and pain-point data reveals high complexity challenge areas. Specific problematic components and subsystems are also illuminated and subsequently evaluated for management, including modularization feasibility investigation and supply chain analysis.

A case study is conducted on high-voltage capacitors, which were revealed by the investigatory process as a critical complexity and risk driver. This study validates the methodology and provides actionable recommendations to executive leadership, enabling progress towards strategic goals. These recommendations include employing a modularization strategy to a portion of the product portfolio in order to influence supply chain dynamics to increase HIGHVOLT’s influence and autonomy.

Results of this project include identification of thirteen critical high-impact areas with recommendations for further action. Specific high-risk drivers are also highlighted; particularly, reliance upon single-source suppliers. A deep investigation to alleviate the single source supply issue for high-voltage capacitors results in a novel technical solution that increases modularization to reduce variants in the product portfolio while maintaining essential flexibility and improving HIGHVOLT’s supply chain dynamics.

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# TABLE OF CONTENTS

**ABSTRACT** ...............................................................................................................................3

**ACKNOWLEDGEMENTS** ............................................................................................................5

**TABLE OF CONTENTS** ..............................................................................................................7

**LIST OF FIGURES** ....................................................................................................................9

**LIST OF TABLES** ..................................................................................................................10

1 **INTRODUCTION** ..................................................................................................................11
  1.1 **COMPLEXITY MANAGEMENT AT HIGHVOLT** ..............................................................11
    1.1.1 Project Context ...........................................................................................................11
    1.1.2 Project Motivation ....................................................................................................11
  1.2 **PROJECT APPROACH AND METHODOLOGY** ............................................................11
  1.3 **MAJOR FINDINGS AND CONTRIBUTIONS** ...................................................................12
  1.4 **THESIS ROADMAP** .......................................................................................................13

2 **FOUNDATIONAL KNOWLEDGE AND ANALYSIS** ..........................................................14
  2.1 **HIGH-VOLTAGE TEST EQUIPMENT INDUSTRY ANALYSIS** .....................................14
  2.2 **HIGHVOLT PRÜFTECHNIK DRESDEN GMBH** ............................................................18
    2.2.1 History [4] ................................................................................................................18
    2.2.2 HIGHVOLT Today ......................................................................................................19
    2.2.3 HIGHVOLT Product and Service Portfolio .................................................................19
    2.2.4 HIGHVOLT Process Overview ...................................................................................24
    2.2.5 The HIGHVOLT Customer ..........................................................................................25
    2.2.6 Culture and its Role at HIGHVOLT ............................................................................26
       Chapter Conclusion .............................................................................................................28

3 **LITERATURE REVIEW** ........................................................................................................29
  3.1 **THE CHALLENGE OF DEFINING COMPLEXITY** ..........................................................29
  3.2 **COMPLEX FEATURES OF COMPLEXITY** .....................................................................32
  3.3 **COMPLEXITY COSTS** ....................................................................................................35
  3.4 **GUIDING PRINCIPLES BEHIND THE METHODOLOGY** ............................................36
       Chapter Conclusion .............................................................................................................38

4 **COMPLEXITY MANAGEMENT APPROACH** .....................................................................39
  4.1 **PAIN POINT COLLECTION AND ANALYSIS** ..............................................................39
    4.1.1 Data Collection ..........................................................................................................39
  4.2 **CORE PROCESS FLOW MAPPING** .................................................................................41
    4.2.1 Mapping the As-Is Process ..........................................................................................41
    4.2.2 Validation of the As-Is Process Flow Map ..................................................................43
    4.2.3 Initial Findings ............................................................................................................43
  4.3 **SYNTHESIS OF PAIN POINTS AND PROCESS FLOW** ..............................................44
    4.3.1 Mapping Pain Points to the Process Map ...................................................................44
    4.3.2 Type Classification of Pain Points ..............................................................................47
    4.3.3 Impact Area Classification Method ............................................................................49
# LIST OF FIGURES

Figure 1: Volatility of machine tool orders with respect to GDP change. Example of supply chain bullwhip effects [2] .............................................................................................................................16

Figure 2: Market test objects, test cases, and HIGHVOLT solutions [5] ........................................20

Figure 3: Alternating current test systems examples [5] ......................................................................22

Figure 4: Aspects of complexity in product design [14] .................................................................31

Figure 5: Wilson and Perumal’s framework for managing complexity [13] ......................................32

Figure 6: Complexity curve demonstrating ‘tipping point’ of complexity [16] ............................33

Figure 7: Structural complexity increasing with modularity [15] ..................................................35

Figure 8: Overlapping responsibilities of product, process and supply chain activities [19]. .36

Figure 9: FAT 3-DCE Model adapted from MIT working paper by Morris Cohen and Charles Fine, August 2000 [19] ..................................................................................................................................37

Figure 10: Excerpt of the process flow map ..................................................................................42

Figure 11: Example of clustering of pain points ..............................................................................45

Figure 12: Large impact area pain points ......................................................................................46

Figure 13: Example of cause-victim linkages .................................................................................47

Figure 14: Temporal guide for leadership decision making ..............................................................49

Figure 15: Impact area action level within HIGHVOLT .................................................................50

Figure 16: High Impact Areas. Number of pain points and correlations between PIAs and SIAs .................................................................................................................................................52

Figure 17: High impact areas with enabler impact areas ..................................................................53

Figure 18: Partitioned DSM demonstrating projects which may be undertaken together ..............54

Figure 19: Theoretical Gantt chart demonstrating critical path time determination .........................57

Figure 20: High-voltage AC capacitor used as a voltage divider (right), HV filter, and coupling capacitor [24] ........................................................................................................................................58

Figure 21: Structural decomposition of AC HV capacitors ...............................................................59

Figure 22: Functions of AC capacitors ............................................................................................61

Figure 23: Functional decomposition of AC HV capacitors .............................................................62
LIST OF TABLES

Table 1: Twelve critical teams surveyed for pain point collection ...........................................40
Table 2: Type classification of pain point data ........................................................................48
Table 3: Thirteen impact area classifications ..........................................................................49
Table 4: Impact area analysis reflecting number of teams reporting, primary and secondary impact area classifications .........................................................................................51
Table 5: Correlations matrix displaying interactions between impact areas .........................52
Table 6: Rated voltages and capacitances (types in bold letters are preferred) [24] .............64
Table 7: List of assumptions for path 1 ..................................................................................65
Table 8: Available capacitive modules path 1 .........................................................................65
Table 9: Path 1 portfolio options with system voltage and total capacitance .........................66
Table 10: Available capacitors using series and parallel connections .....................................67
Table 11: Path 2 assumptions that differ from path 1 ...............................................................68
Table 12: Available capacitive modules path 2 .......................................................................68
Table 13: HV AC capacitors with series connections up to three capacitors .......................68
Table 14: Portfolio additions using two like modules in parallel connection .........................69
Table 15: Portfolio additions using three like modules in parallel connection .......................69
1 INTRODUCTION

1.1 Complexity Management at HIGHVOLT

1.1.1 Project Context

HIGHVOLT Prüftechnik GmbH, located in Dresden, Germany has been an industry leader in design, development and manufacturing of high-voltage test equipment for over 110 years. HIGHVOLT operates in a unique market producing highly specialized test suites built to robust and highly individual customer specifications with a repetition rate near zero. These conditions naturally lend to high costs and long delivery time. Senior leadership desires an investigation into the reduction of cost, delivery time and management of risk.

1.1.2 Project Motivation

Diagnostic analysis and exploration of potential means for cost reduction and time savings are necessary to achieve the strategic goals of the company. First, a deep understanding of the current state is formulated. The objective is to create a methodology to reveal, analyze and manage complexity in order to provide actionable recommendations to decrease cost, improve delivery time and reduce risk.

We hypothesize that by treating complexity holistically, beginning at a high level collection of process, product and organizational complexity we can achieve a broad and highly effective management of the complexity in the system. Through the proposed method we posit that the more efficient management of complexity at HIGHVOLT will result in valuable time and capital savings.

1.2 Project Approach and Methodology

Two primary techniques are employed: thorough core process flow mapping and pain-point data collection from critical stakeholders. Process flow mapping is critical to understanding where complexity enters the process, resides and is correlated to other process steps. Pain-point collection and analysis aim to reveal inefficiencies in order to target causal factors. Together the process flow mapping and pain-point data is synthesized to illuminate challenge areas and highlight issues that, if alleviated, would reduce complexity in multiple areas. Specific problem components and
subsystems are revealed employing these techniques and are then assessed for modularization feasibility.

Several common threads discovered via collection of key stakeholder data suggest specific high-complexity areas warranting investigation. The core process flow is mapped using existing company documents, subsequently validated by experts and used to guide pain-point classifications. Methodology for pain-point collection is developed and 12 critical teams chosen for survey. In total, 155 pain-points were collected, analyzed and classified. The pain-points are then mapped to the process flow, showing concentration areas, large-impact points and cause-victim relationships.

Investigation of a critical complexity and risk driver is done in case-study manner to validate the methodology and provide actionable recommendations to leadership, guiding progress towards strategic goals. This investigation employs a modularization strategy to a portion of the product portfolio in order to influence supply chain dynamics in such a way as to increase HIGHVOLT's influence and autonomy.

1.3 Major Findings and Contributions

Thirteen critical high-impact areas are identified with five significantly correlated projects proposed to executive level leadership. High-risk drivers are also illuminated; particularly, reliance upon single-source suppliers. A deep investigation of methods to alleviate the single source supply issue for high-voltage capacitors is conducted. A new technical solution is optimized through increased modularization to reduce variants in the product portfolio while maintaining essential flexibility. The resulting solution affords the opportunity to negotiate with new potential suppliers and improves HIGHVOLT's bargaining position with the existing supplier. Effectually, the high-voltage capacitor case study validates the methodology employed while enabling cost savings, time conservation and risk-management for HIGHVOLT.

This thesis aims to support methods to manage complexity at HIGHVOLT and provide generalizable findings helpful to other business and engineering applications.

In summary, the primary contributions of this project are:
- provide a framework with which to comprehend holistic complexity in a company
- demonstrate a methodology for discovery of complexity drivers
- suggest classification strategies to make the complexity data useful for action
- propose a method for ranking complexity drivers
- suggest actionable projects to help alleviate complexity where excessive (by reduction or reallocation)
- provide a case study on a risk and complexity driver with results validating the methodology of discovery
- demonstrate a useful case of product portfolio modularization to influence supply chain dynamics
- suggest a novel reason for modularizing a product portfolio—to alleviate a single-source supply issue

1.4 Thesis Roadmap

The thesis structure mirrors the research approach taken to a good degree. Chapter 2 will provide foundational knowledge and analysis to establish a base upon which to develop the analytical framework. A literature review is presented in Chapter 3 to summarize relevant academic work and provide justification to some of the researcher's choices. These choices bear importance on the solution framework which follows in Chapter 4. The chapter continues with an in depth explanation of the research method and preliminary results. Chapter 5 deep dives into a case study on a critical complexity and risk driver that was discovered via the framework employed and described in Chapter 4. Chapter 6 concludes this thesis by providing conclusions, recommendations, future work and progress to date.
2 FOUNDATIONAL KNOWLEDGE AND ANALYSIS

This chapter will set the stage for the research environment and provide insight into the high-voltage test equipment sector. A brief overview of the industry at large and a discussion of HIGHVOLT's position in the landscape frame the discussion. A short history of the company is provided to demonstrate the origin of the market differentiators of HIGHVOLT—reputation, customization and quality; and give background as to why HIGHVOLT is respected as the best technical solution provider. Some key elements of the company's current portfolio are discussed in greater depth to give clarity to the uniqueness of the offerings and a few of the product challenges faced. Next, a high-level process flow description is offered with emphasis placed on attributes helpful in the research area of complexity management. Then, because HIGHVOLT's customers have strong influence in the execution of the business, we will spend some time explaining their individuality and needs.

The chapter concludes with an in-depth and important discussion about the role of culture at HIGHVOLT; both in the company culture sense and in that of the national norms. This cultural discussion will prove a linking thread woven throughout the analysis and recommendations and in such, is critical.

2.1 High-Voltage Test Equipment Industry Analysis

HIGHVOLT Prüftechnik Dresden GmbH has dominant market share in the high-voltage test equipment market. The company estimates a total market share between 28-35% of global demand. Two primary competitors, Haefely Hipotronics of Switzerland, and Chinese companies providing solutions under various trademarked names (one being Beijing Huatian Mechanical-Electrical Institute, Co. Ltd.) share notable portions of the remaining market. HIGHVOLT is known to be the highest quality and reliability supplier with Haefely Hipotronics next and the Chinese companies as the lesser in quality and cost option. There are relatively few competitors for the market share in the sector but buyers retain the option of purchasing on quality or on cost.

Global transformer market data serves as our best proxy to explain the behavior of the high-voltage test equipment market, on which there is no specific, publically available research data. This data most closely mimics the high-voltage test
equipment industry because the transformer market is dependent on the high-voltage test equipment market for qualification of their systems. The major market drivers are: infrastructure investments, updated regulatory policies, replacement of aging systems, industrial and commercial growth and the growth of smart grids. The primary restraints on the market are: raw material cost volatility, entry by Asian companies into the market, and macroeconomic fluctuations [1]. Due to the noted market drivers, particularly infrastructure investments driven by positive economic growth, the total global transformer market is expected to have a compound annual growth rate over 4% from 2016-2022 [1]. We can expect the high-voltage test equipment industry to mimic this growth over the period, but with an increased volatility over time as constraints like economic instability arise.

As Anderson, Fine and Parker explain, minor positive changes in national gross domestic product (GDP) produce amplifying changes through upstream industrial suppliers. HIGHVOLT, as a supplier to major infrastructure development industries, including the transformer market, is subject to this volatility; experiencing what is commonly known as bullwhip effect [2]. For example, during times of economic growth, nations make repairs or updates to electrical grids and / or undertake large expansions of the grid. Therefore, more high-voltage test equipment is initially needed to service the first tier transmission grid (greater than 145kV) during the 'boom' times. Due to a rush to provide for this growing market, the demand is amplified at the first tier level. As these first tier investment projects conclude second tier industries, like primary distribution grid (10 to 145kV) manufacturers, require high-voltage test suites which continues to drive amplification of demand. Eventually, coinciding with more austere economic times, infrastructure projects decrease and the demand for high-volt test systems does, dramatically, with them.

Figure 1 provides a graphical example of this phenomenon using machine tool sales, shipments and automobile sales. As GDP rises, machine tool orders explode in anticipation of future automobile demand increases. The cyclicity for the machine tool manufacturer mirrors that of the GDP, but to a much more amplified degree. Given the truly global market serviced by the few suppliers of high-voltage test suites, knowing the demand correlation to GDP is not always enough to guide forecasting as economies in Asia can be booming while western economies are slowing. These
dispersed economic fluctuations drive the cyclic but unpredictable demand in the high-voltage test equipment market.

![Graph showing GDP, MT Orders, MT Shipments, and Vehicle Sales over a period from 1971 to 1995. The graph illustrates the volatility of machine tool orders with respect to GDP change, an example of supply chain bullwhip effects.](image)

**Data Sources:**

**Figure 1:** Volatility of machine tool orders with respect to GDP change. Example of supply chain bullwhip effects [2]

With the market considerations understood, we transition to an explanation of the average customer and common industry concerns. High-voltage test suite customers desire a whole-suite test solution that will last in excess of thirty years; often up to 50 years. The technical solutions offered to meet the customers' needs operate at the limits of physics and material properties. Due to the nature of their function, test systems have the potential to do harm to persons and property if not properly manufactured and maintained. Also, often firm regulations dictate the test and qualification of electrical equipment to protect the public. Regulation and strict safety requirements combine to produce a market which tends to value high-quality over low-cost.

Few new entrants exist in the high-voltage test equipment manufacturer space for several reasons. High-voltage equipment manufacturing and service require
specialized knowledge and the best manufacturers use proprietary methods developed over years of experience. Also, new entrants face high capital investment requirements in infrastructure. The time and cost to enter the market keep the threat of new entrants low. However, this feature appears to reinforce the importance of developing cost advantages where able, while maintaining technical superiority and quality.

Of particular importance to this research, supplier power in the market is very strong. Components of high-voltage test systems are often sourced from suppliers in very low quantities and to customized specifications claiming very high performance quality. These suppliers are also quite limited in number as they are (similarly) producing very technical niche components. These components, however, also are used in larger scale electrical equipment manufacturing and thus the high-voltage equipment manufacturer is generally a very small client for the supplier. This empowers the supplier and commonly results in significant cost and long delivery times for high-voltage test equipment manufacturers.

Globally, the recent availability of Chinese made high-voltage test equipment has produced fairly modest shifts to the market share. Interestingly, the Chinese manufacturers claim their product quality is proven with HIGHVOLT test equipment. Most commonly, the introduction of a Chinese producer has driven some degree of higher price sensitivity in the customer base and has not caused major movement towards the lower cost alternative. Though the Chinese competitor has not yet extensively infiltrated the traditional customer base of HIGHVOLT and Haefely Hipotronics, it does appear they are likely to be able to support their own national demand for test suites in the near future. Most likely, soon Chinese customers will not need to source from external companies in the industry. Chinese manufacturers are being encouraged to pursue foreign markets, often with governmental financial support which could cause a shift in market share. However, foreign markets may use import controls to manage this issue [3].

In summary, the high-voltage electrical test equipment market has a few key competitors operating in an environment that is cyclical, experiences significant bullwhip and has high barriers to entry. The focus on quality is native to the high-costs associated with a potential component failure and governmental regulation.
Supplier power is strong due to the relative size of orders from high-voltage companies and the degree of customization necessary. Global market share may experience a shift in the years to come with Chinese manufacturers now present and pursing low cost strategies. This market analysis frames the environment in which HIGHVOLT operates.

2.2 HIGHVOLT Prüftechnik Dresden GmbH

2.2.1 History [4]

HIGHVOLT has more than 110 years of experience in the design, development and manufacture of high-voltage test equipment. The rich history begins in 1904 with the founding of Koch & Sterzel, a company focused on the manufacturing of transformers and high-voltage test equipment. The technical strength and engineering prowess of the company was retained during the years of the German Democratic Republic, with the company serving mostly Soviet-bloc countries’ high-volt test needs. After World War II, the company was renamed Transformatoren- und Röntgenwerk (TuR) and continued supplying test equipment for a broad range of customers with retained focus on the Soviet-bloc countries. TuR was purchased by Siemens AG following the reunification of Germany and made an independent company, HIGHVOLT, a few years later. In 2002, the Reinhausen Group acquired HIGHVOLT.

The reputation of the company as the highest quality manufacturer in the industry began with a series of important historical achievements. The early years of Koch & Sterzel saw such achievements as the world’s first 1 MV cascade transformer and impulse generators up to 2.5 MV. The state of the art technology of the day was provided to research universities including the Massachusetts Institute of Technology and the Technische Universität, Dresden. In 1990, TuR produced a high-volt test system capable of 3 MV alternating current and 7.2 MV impulse voltages making it the largest such system in the world. Not long later, HIGHVOLT manufactured the first mobile alternating current test system using static frequency converter technology. HIGHVOLT continues to lead the industry in new technology development and is the first choice of customers pushing the limits of current power distribution technology. The legacy of HIGHVOLT’s past achievements is the foundation upon which its reputation as the industry quality leader continues to stand.
2.2.2 HIGHVOLT Today

Located in Dresden, Germany this 100% subsidiary of the Reinhausen Group continues to be the industry benchmark in highly specialized equipment for manufacture testing, field testing and laboratory research and development of power grid systems worldwide. Today HIGHVOLT has over 240 employees with more than 60% trained in engineering disciplines. They undertake approximately 50 projects a year with very low repetition rates of like projects (near zero). The engineer-led company prides itself in the ability to provide an elegant technical solution to service any customer's need. The work environment is disciplined and morale is high.

2.2.3 HIGHVOLT Product and Service Portfolio

In line with their historical norm, HIGHVOLT maintains a large product portfolio of highly specialized test suites. Broad spanning customer requirements necessitate the extensive portfolio. As test objects (the equipment tested with HIGHVOLT test systems) have become more varied with technological progress and manufacturing advancements the systems provided by HIGHVOLT to perform testing upon those objects have similarly expanded in number and type. Unique solutions are generated for the customer using components in the existing portfolio or custom made to suit the customer's needs.

The high-voltage electrical equipment industry is constantly changing as a result of technological advances. Thus, it is of paramount importance that HIGHVOLT maintain deep roots in the research and development sector as well as relationships with companies pushing the current limits of power grid technology. For example, if a transformer manufacturer is pursuing a novel technical design for a transformer they will require appropriate test equipment (from HIGHVOLT or a competitor) early in their own research and development stage and certainly more if the new design should go into full scale production. This interesting feature of the industry presents a non-trivial challenge to HIGHVOLT: they must first observe and understand industry trends and then accelerate out ahead of the industry leaders to ensure their portfolio is primed to deliver test equipment to meet the emerging needs of the future customers. This situation drives in-house research and development projects and is causal in some of the expansion in the product portfolio.
HIGHVOLT supplies specialized test equipment suites to customers designed to their individual needs be they in alternating current, direct current, impulse voltage, or impulse current test systems in either mobile or stationary variants. Accompanying measuring systems are provided to the applicable test suites. Test systems can take from approximately six months to over a year to build. Stationary test system variants are housed in test halls akin in size to medium aircraft hangars and much more technical in construction specification. These systems cost six figures on average, but into seven figures with complete consultancy, design and greenfield hall construction. Figure 2 provides a summary of the industry test objects, test cases and HIGHVOLT solutions.

![Figure 2: Market test objects, test cases, and HIGHVOLT solutions [5]](image)

An example use case is provided next to afford the reader insight into a very niche field. In recent years, offshore windmill farms have become more prevalent. If you are an energy company installing and profiting from these vast arrays at sea, energy transmission efficiency is of utmost importance. Minor energy losses in the cable over time can result in millions of dollars lost, not to mention the losses that are possible in the case of a transmission cable failure. As the owner of the windmill farm, you would require the highest, proven cable quality to manage the risk of resource downtime or energy discharge over time. HIGHVOLT provides test equipment to high-voltage cable
manufacturers so they are able to qualify their cable to be installed as part of this booming green energy sector. HIGHVOLT also provides the windmill farm company a mobile test unit to test cable in real time operation or to assist in isolating existing problems. This provides just one example; other customers, as shown above in Figure 2, are transformer manufacturers, research laboratories and more.

To illuminate the challenges and direction of this project it is critical to have visibility to the complexity of the product portfolio. As previously mentioned, strategic direction suggested by leadership is that the product portfolio should be modularized and condensed to reduce cost and delivery time. Whereas the solution portfolio should remain constant and be constrained from extension. However, upon further inspection it becomes clear that the customers served by HIGHVOLT require highly specialized equipment which does not lend itself to being modularized in a broad, whole-portfolio, manner. As seen in Figure 2, test objects vary widely with the offered solutions varying to an even greater degree. Figure 3 shows examples of just the alternating current test systems available in the portfolio. For examples of the resonant systems, direct current systems, mobile systems and control and measuring systems as well as available accessories see Appendixes A, B and C. These figures give perspective to the size and complexity of the test suites and use cases produced by HIGHVOLT.
AC TEST SYSTEMS

TRANSFORMER BASED SYSTEMS 50/60 HZ FOR GENERAL APPLICATION

WP with PEOI
- Insulating case transformers
- For low power applications
- Compact size

WP with PEO
- Transformers in steel tank
- For higher power applications
- Continuous operation

WP G and WPG G
- Oil or SF₆ insulated transformers
- For GIS/OIL testing
- Winding temperature monitored

RESONANT TEST SYSTEMS 50/60 HZ FOR HIGHER POWER

WRM
- Modular HV reactors
- For testing cables and power transformers
- Parallel and series connections

WR
- Steel tank HV reactor
- For testing capacitors, MV cables and generators

WRU
- Steel tank HV reactor
- For testing MV and HV cables
- Internal tap changer for optimum power adaption

TEST SYSTEMS WITH FREQUENCY CONVERTER FOR TRANSFORMER TESTS

WV
- For testing power transformers up to 2000 MVA and shunt reactors
- Mobile and stationary use

HVCC capacitor bank
- Manual or automatic switching
- For testing power transformers up to 2000 MVA
- Mobile and stationary use

DITAS
- For testing distribution transformers up to 5 MVA
- Mobile and stationary use
- Fully automated system available

Figure 3: Alternating current test systems examples [5]
In addition to test system products, HIGHVOLT provides consultancy service to develop unique solutions with customers. This service is particularly useful in large-scale, greenfield and new technology applications. It involves sending teams of subject matter expert engineers to evaluate a customer’s needs, develop plans (often on location) and design uniquely optimized test solutions. The consultancy continues through erection and commissioning of the system to the training of the company’s test system operators. This service demands a great deal from the HIGHVOLT experts on the team and adds another layer of complexity to the company’s offerings.

HIGHVOLT also provides the planning and design expertise necessary, as well as the test equipment necessary, for upgrade and overhaul projects. In cases where customers are looking to reduce cost they often request to reuse existing components (frequently from other suppliers) and integrate them with new HIGHVOLT components. These upgrade projects introduce significant engineering challenges and require even more extensive coordination efforts between HIGHVOLT and the customer. These upgrade projects typify the level of complexity present in the product and service offerings of HIGHVOLT; no two projects of this type are ever the same.

Software development and integration into test system suites is of growing importance to customers. HIGHVOLT now offers extensive software customization and integration with their test systems. Customers have increasingly wide-ranging requests which result in highly labor intensive software projects. The software offerings go beyond data capture and presentation to data analytic packages and even off-site analysis and long term software upgrade support. These test system accessories cater to the traditional HIGHVOLT customer that desires fully customized solutions and result in increased cost and complexity for HIGHVOLT.

Lastly, calibration, maintenance, service and repair are also provided by HIGHVOLT. A certified calibration laboratory is continually available on site in Dresden, Germany with the additional option for customers to request worldwide on-location calibration tests. Repair or servicing requires that spare parts are kept available or easily acquirable. Since HIGHVOLT systems have such long lifespans customers may call with a repair request on a component decades old. Telephone and remote online technicians are made available to assist the customers with any problems they may face. Employees with extensive know-how are kept in reserve to answer to immediate
on-site assistance needs of the customers. These services are of high importance to the customer and they often influence the customer's decision to select HIGHVOLT as their solution provider. Thus, these aspects of the business are vital to maintaining market share and also introduce significant complexity for HIGHVOLT making them an area to focus on for complexity management.

### 2.2.4 HIGHVOLT Process Overview

As noted in the introduction chapter the core processes at HIGHVOLT were extensively evaluated and proved critical in locating, understanding and mitigating complexity within the system. Here a general overview of the process is provided as context for the continued discussion. This facet of the company is also inseparable from the history, product and services, customer and culture discussions in this chapter. This overview helps to build the holistic view of the company for the reader.

For overview simplicity we will begin the process (which is actually started from several places along the process flow) at customer contact. Customers are sought via several avenues: repeat business, government contracts, active marketing campaigns, conventions, academic relationships, etc. HIGHVOLT has significant brand recognition in their sector as a result of their high quality and reliability. Typically, HIGHVOLT receives customer requests for offers based on this industry reputation and word of mouth while they also actively seek public tenders (who are often required to seek three different quotations according to European law).

Upon receiving a request, the sales team then works with the engineering department to develop a specialized technical solution to the customer's needs (as discussed, customer needs vary significantly based on the test object). When a solution is available or a research and development project is agreed upon the customer receives the official offer from the sales department. This offer is often iterated upon with the customer and can continue in discussion phase for up to six years prior to moving ahead. With customer approval the engineering department undertakes the lengthy engineering work of design and documentation.

With a finalized design the operations team can begin the qualifying of suppliers (if required), ordering, receiving, inspection, construction and initial testing of the system. Customers attend factory acceptance testing onsite and with the help of the
project team plan for delivery to the customer location. Erection and commissioning are managed and conducted by HIGHVOLT engineers at the customer site. Lastly, training is offered at the customer site to ensure proper use and maintenance of the test system.

In the event of troubleshooting requests from existing customers, refurbishment, or upgrade often the process begins with the service department before continuing on the flow described above.

The above description is idealized in that it does not describe the many rework loops and customer interventions via change requests. Many of the approximately 50 projects HIGHVOLT executes a year take a unique path to completion due to the highly specialized nature of the system. Deeper investigation of the process induced complexity is found in Chapter 4.

2.2.5 The HIGHVOLT Customer

HIGHVOLT's customer base ranges broadly from cable manufacturers to research and development laboratories at leading universities. Research and development testing, manufacture testing, field testing and maintenance testing are just some of the test requirements customers of HIGHVOLT face. A manufacturer of cables may require only one type of test profile, whereas, academic institutions and research facilities desire highly versatile systems capable of many waveforms and voltages. Customers request systems that will last thirty to fifty years while maintaining the ability to adapt with changes in technology. The customer demand of specialized solutions drives the high degree of product complexity, long delivery times and high cost and is also HIGHVOLT's market differentiator. The value HIGHVOLT uniquely brings to market is the individualized complex systems they offer. These needs directly influence the direction of this project. This analysis leads us to believe broad product modularization strategies aimed at reducing complexity are unlikely to continue to meet the customers' needs if they reduce capabilities of the system. If HIGHVOLT is to continue to serve the same customer base, they must continue to offer highly customized products. Attempts at complexity management should be undertaken while prioritizing retention of the individualized functionalities expected by the customer.
2.2.6 Culture and its Role at HIGHVOLT

Culture will be shown to have significant effects upon the current challenges facing HIGHVOLT and should not be overlooked as an area to drive improvement in order to meet the strategic goals of the company. HIGHVOLT’s culture is both a great strength and a complexity driver worthy of mitigation. Culture and norms prove to be the thread linking the data and analysis to findings and recommendations. Therefore, a deep understanding of this aspect is necessary for the reader to fully appreciate the intricacies of the project as well as the ramifications of the recommendations.

A 100-year history in a unique, highly technical field in a geographic area with prominent national identity norms forms an interesting basis for the current company culture. The company weathered such trying events as two world wars, a soviet-era communist dictatorship and a transition to democracy that came with German reunification with relative grace. Their heritage of excellence in engineering persisted throughout all the dramatic changes of the period. Given their cultural heritage and highly complex product line it is not surprising that they maintain a tightly hierarchical structure with high regard for academic reputation. Thus, the organizational culture at HIGHVOLT can be described as in line with German national cultural dimensions first described by Hofstede: strong workforce power distance (hierarchy), moderate uncertainty avoidance and moderate individualism [6].

One of the highly beneficial traits specific to HIGHVOLT is the educated and competent workforce. Every employee from the CEO to the frontline operations worker is deeply trained in their job and has high personal expectations for the performance of their duties. Much of the knowledge required for repeated orders and daily activities is tacit. Employees work extremely well autonomously on their known, assigned tasks. This, however, causes difficulties when there are deviations in projects requiring collaboration or ownership of new tasks. New knowledge is developed by individuals regularly in their duties, but the organization is not always well suited to disseminate and amplify the findings [7]. This leads to various challenges, including an example discussed in Section 6.1.2 of this work, where a company expert had existing knowledge useful in development of a component modularization plan but had not yet developed his ideas due to a lack of frameworks for knowledge creation and capture.
At the department level, rigid functional hierarchy exists with the individual departments quite siloed. These siloed departments experience disparate power and control over each other with the engineering department being dominant. This design, though understandable as result of the heritage of the company, sometimes inhibits the concerns of the operations and sales departments from being heard. As a result of this structure, the engineering department often exerts decision rights over such varied topics as timeline structures and strategic decisions which may be better managed by a different department. The siloing and rigidly hierarchical structure also cause significant communication flow breakdowns and rework loops. Lastly, a surprising feature is that even in the rigid system often task responsibilities are not assigned causing a lack of institutionalized accountability.

Due to historical development and the influence of the engineer-centric culture, current strategy (though not the formally expressed strategy) is to engineer the best high-voltage test equipment and then do whatever necessary to produce and sell them. This strategy results in far greater emphasis paid to engineering tasks than business tasks, like those run by the operations and sales departments. While this model worked well for HIGHVOLT historically, the recent growth of the company and acquisition by Maschinenfabrik Reinhausen necessitate improvement. To fully address the strategic goals of HIGHVOLT to manage complexity to reduce lengthy delivery timelines and high costs attention must be paid to these imbalances. Introduction of a Head of Business Development position has shifted focus to addressing these imbalances, enabling the existing emergent strategy to become a more deliberate emergent strategy. This project also illuminates the imbalance, and analyzes the qualitative effects which result, while continuing along HIGHVOLT's path of deliberate strategic learning [8].

Positively, the corporate and employee values appear generally aligned. Importance is placed on the value of quality work, demonstrating respect for one another, maintaining a congenial environment, and honoring personal time. One noted area of friction is the respect of the work done by operators and sales team members who are not of engineering background, which happens to include most of the women in the workplace. Some findings from this research suggest ways to work towards the cultural shift needed in this area and were strongly supported by HIGHVOLT's leadership. Similarly, front-line workers and non-technical employees have limited
voice rights, leading to lack of empowerment to drive improvement.
Recommendations from this project also address employee empowerment and were
embraced by senior management immediately. As one might expect, voice of dissent is
heard only in one-on-one meetings, not in group settings. Thus, the data collection
methodology for the project takes this into account and is primarily one-on-one via
interviews.

Chapter Conclusion
In this chapter we provided fundamental background information critical to the
understanding of the project, its direction and findings. A market analysis was
provided to introduce the landscape within which HIGHVOLT operates. The
company's history, product and service portfolio, customer base and culture were
described with key features more closely analyzed in order to support the follow-on
details of the research methodology, findings and recommendations.
3 LITERATURE REVIEW

This chapter will provide a brief discussion of academic work relevant to the project. First, a discussion regarding the challenges of defining complexity is explored and a decision about how ‘complexity’ will be used in this research is offered. Then, a few specific features critical to this research on how complexity is itself complex will be presented. Specifically, that: sometimes complexity is positive, local minimization of complexity does not always reduce system complexity and that modularization does not always make the system less complex. Then, we will briefly support the intuitive assumption that complexity is expensive. Lastly, insights into the foundational business strategy works used to inform the researcher’s methodology and recommendations is provided.

Of note, significant quantitative work has been done on component complexity, along with robust metrics proposed to quantify complexity as it relates to a specific engineered system. The work of this project, though, approaches the system complexity from a top-down, time constrained perspective so as to best afford the opportunity to leadership to make rapid decisions to manage complexity. Further work applying the complexity metrics found in previous work, especially the work done on integrative complexity by Sinha, Suh and de Weck, and product family complexity by Kim, Kwon, Suh and Ahn, would be helpful in expanding the generalizability and quantification of the approach found in this research [9] [10]. Time and data collection constraints prohibited the researcher from pursuing further quantification via Design Structure Matrix methods (DSM) and complexity metrics but this avenue is noted as excellent follow-on work stemming from this project. More discussion of these methods with examples can be found in Section 4.3.4 and the Future Work portion, Section 6.3.

3.1 The Challenge of Defining Complexity

A single accepted definition of ‘complexity’ or methodology for ‘complexity management’ remains elusive for both engineering and business academics. It is reasonable, however, to acknowledge ‘complexity’ has both managerial and engineering implications. As such, industries tend to develop their own meaning for the term to suit their individual application. For example, some of the first work done
to generate a method to conceptualize and measure complexity was undertaken by software engineers in which the number of paths through a software program were used as the measure [11]. As one might expect, it is easier to define complexity in some fields than others.

Systems engineers have long debated and desired a way of defining complexity, thereby making it meaningful for quantitative measure. Unfortunately, those considered preeminent in the field still manage to find, “there are so many facets to complexity that there is no one definition – it depends on the perspective” [12]. The challenging nature of the problem does not devalue the importance of attempting to grasp and manage complexity. Understanding complexity in hopes of managing it is top priority in many fields. This is one reason we have undertaken the challenge of developing a way to holistically discover complexity to produce meaningful recommendations on how to manage it.

Further demonstrating the unclear treatment of complexity is the desire to create a leading indicator for complexity and inability to do so. A team of experts from Massachusetts Institute of Technology’s Lean Advancement Initiative (LAI), INCOSE, PSM and SEArI determined that complexity would be a highly useful leading indicator in their second version of the “Systems Engineering Leading Indicators Guide” yet found it currently unmanageable to make a meaningful indicator for several reasons. Below is a direct excerpt of the most applicable reasons to this research; further elucidating why defining and measuring complexity is so challenging.

- “Given the lack of clarity on a common definition for complexity, it is not clear how we will know how to have a valid measure of it.”
- “Should the measure address the complexity of the systems being built (product elements and interfaces, e.g.) or the development project building such a product (tasks and schedules), or perhaps a combination of these approaches?”
- “How much of the measure should address structure (size, connectivity, and patterns) vs. dynamics (short-and long-term) vs. socio-political complexity?” [12].

These experts also clearly suggest complexity resides in several spaces (within a product, a process, and in the human interactions) and is static and dynamic.
Complexity, broadened from a systems engineering application to a business context, is even more challenging to capture. In this spectrum, understanding complexity relies increasingly on qualitative information. This is one justification as to why we begin with Wilson and Perumal’s belief that three main categories of complexity exist: product, process, and organizational [13]. This framework marries well to the challenges expressed above from the systems engineering community. The addition of market complexity as a fourth ‘field of complexity’ by Lindemann completes the complexity landscape and will serve as our framework [14]. This practical approach to the nature of complexity fits the holistic approach of complexity management desired by the leadership of HIGHVOLT and the intuition of the researcher to yield rapidly actionable findings. Examples of the four fields of complexity is provided in Figure 4.

![Figure 4: Aspects of complexity in product design [14]](image)

Accepting these four fields of complexity, we recognize that businesses should be aware of complexity introduced from all of them, while acknowledging, as Lindemann argues, “in practice the market mostly dominates” [14]. Since market influences cannot generally be controlled by the enterprise we focus our efforts on understanding the complexity the market introduces and adapting strategy to mitigate its harmful effects rather than trying to directly manage the complexity induced.

Combining the market analysis (found in Chapter 2.1) with a profile of the targeted customer base of HIGHVOLT (found in section 2.2.5) we conclude that the market and customer require a high level of customization and cutting-edge technology. The result is a lack of control over the complexity introduced from the market, thus we consider this complexity ‘external’. Instead, we focus our holistic investigation to the
internally effectible complexity in process, organizational, and product while looking for opportunities to influence market complexity when possible.

With the four fields of complexity in mind we can introduce a definition of a complex system: numerous connected, interfaced, and related elements and / or relationships that require in depth explanation and data to specify and can range in type (numerical, organizational, relationship, etc) [adapted from [15] [14]]. We will consider HIGHVOLT a complex system in its production of high-voltage test equipment. “Complexity” is then used to encompass these complicated and dynamic forces acting upon and within the system. Thus, complexity causes variance, volatility and often temporal delay within a system.

3.2 Complex Features of Complexity

Complexity is itself complex. In this section we will discuss a few of the critical issues regarding complexity as we have defined it above for our project. Wilson and Perumal present a framework for managing complexity noting that there are two choices: reduce the amount of complexity or make the complexity less expensive [13]. Figure 5 below graphically demonstrates this framework with examples of management choices.

*Figure 5: Wilson and Perumal’s framework for managing complexity [13]*
We posit that our methodology reveals complexity; allowing actions to both reduce it where able and make it less costly otherwise. We additionally argue that the terminology 'manage complexity' is more inclusive of initiatives found on the right circle of Figure 5, and more useful in our findings and thus will use 'manage complexity' instead of 'make complexity less expensive'. We justify this adaptation because while managing complexity may involve reducing its cost, it may also include mitigating the risks associated with it. Thus, we find this broadening of 'make complexity less expensive' necessary. We propose that targeting the complexity holistically (rather than targeting singularities) is the most beneficial method. The three following sections afford evidence in support of our chosen method for application at HIGHVOLT.

Sometimes complexity is good

The first key issue to point out about complexity is that sometimes complexity is good. Certainly at HIGHVOLT, complexity of the product portfolio and individual components of the test systems is one of the main market differentiators harnessed. Collison and Jay provide a complexity curve to demonstrate the tipping point of where complexity becomes detrimental (Figure 6, adapted from [16]).

![Complexity curve demonstrating 'tipping point' of complexity](image)

*Figure 6: Complexity curve demonstrating 'tipping point' of complexity [16]*

We also intuitively understand that complexity is good for highly innovative products which may offer advanced or new features. As customer needs evolve good complexity helps to keep up with demands. Error detection and correction can be enhanced with additional layers of complexity. Regulatory and safety additions to a
system can be considered good complexities because they enhance overall safety. The goal for this project is to move back along the complexity curve to a point at where HIGHVOLT is capitalizing on the good complexity and managing or minimizing the bad.

Local complexity minimization does not necessarily minimize system complexity

It is also intuitive that simply optimizing one component of a system may not, in fact, reduce the system complexity at large. Locally minimizing does not necessarily provide overall complexity management benefits. Lindemann explains this systematic scope with an example: “avoiding complexity by reducing variants will only result in positive effects if the associated enterprise processes can be simplified in equal measure” and continues to note that it is best no action be taken until it is assured that the supporting processes can be similarly modified. He also warns that change propagation and new dependencies can cause an increase in complexity [14]. Due to the nature of HIGHVOLT’s business, minimizing complexity on a local or individual component scale is unlikely to make the broad impact required to achieve the strategic goals. Thus providing another reason we elect to focus on the holistic product, process and organizational interfaces for optimization.

Modularization does not always make systems less complex, and you can lose function

Modularization as a strategy to reduce complexity has been frequently employed by numerous fields. It can be thought of as encapsulation of complexity into smaller parts to be better understood. Once divided into the smaller parts, “one can hide the complexity of each part behind an abstraction and an interface” [17]. For our purposes, Baldwin’s definition of module works well: “a unit whose structural elements are powerfully connected among themselves and relatively weakly connected to the elements in other units” [17]. Importantly though, modularizing does not always lead to a reduction in overall complexity and sometimes important function can be lost.

Lindemann acknowledges this risk of modularization noting that “inadequate outcomes and compromised solutions” can occur and that modularization, “can keep manufacturers from offering customer-oriented and specific solutions to the average customer” [14]. Losing customization options will seriously deteriorate the
willingness to engage in business for HIGHVOLT's traditional customers; thus, in our research we are highly sensitive to these concerns. We also acknowledge, as Sinha demonstrates, the idea that against common wisdom, increased complexity can occur with increased modularity [15]. Thus showing that modularization and complexity can be negatively correlated. This is graphically demonstrated in Figure 7.

This knowledge, that modularization does not always reduce complexity and can result in the loss of function, is one reason we rejected the premise that this research would be a complexity minimization project via blanket modularization. As discussed previously, HIGHVOLT customers demand customization and the HIGHVOLT product line is innately complex. Still, we look to all areas in which we can manage complexity. This includes the discovery of a strong case for modularization of a product component which is made in Chapter 5.

3.3 Complexity Costs

From our definition of complexity, we can assert that complexity causes increased costs. A mental comparison of low complexity vs. high complexity yields a generalization that more interfaces, interactions, parts, etc. will cause an increase in cost of component as well as time to produce it. Rechtin formalizes this idea that the more complex a system is the more difficult it is to build and use and thus also more expensive. He also notes some of this increase in cost is a result of needing to utilize more specialized experts [18]. As we assert that increased complexity increases cost, we will target managing complexity to address the strategic goals of this project: reduce cost and delivery time while managing risk and while continuing to meet the needs of the HIGHVOLT customer. This focus also stems from internal strategic knowledge within the company which suggests reducing delivery time and active risk
management will improve the cost situation more than managing material or labor costs.

3.4 Guiding Principles Behind the Methodology

Our approach to treating the strategic goal of complexity management at HIGHVOLT is built foundationally upon the work of Charles Fine on the interconnectedness of product, process and supply chain. His book, *Clockspeed*, guides the research while our methods and results found in Chapters 4, 5, 6 clearly demonstrate the fundamental linkages between the entire system architecture as he proposed. His work is also used in discussion of modularization strategies as they apply to entire systems. In Section 6.3, we use his findings to explore the topic of vertical integration strategy.

Upon first inspection, the system at HIGHVOLT exemplifies the interconnectedness of the product, process and supply chain. Figure 8 demonstrates the overlapping responsibilities between these activities.

![Figure 8: Overlapping responsibilities of product, process and supply chain activities](image)

Our methods and recommendations are formulated with acknowledgement of these overlaps. Fine provides further refinement of the overlapping areas by subdividing tasks to highlight the need for concurrent treatment in what he calls the Focus, Architecture and Technology 3 Dimensional Concurrent Engineering Model (FAT 3-
DCE Model) which is shown below in Figure 9. We accept that these aspects must be actively managed concurrently with regard for their linkages and dependencies in order to resolve the most beneficial solutions.

![Diagram](image)

**Figure 9: FAT 3-DCE Model adapted from MIT working paper by Morris Cohen and Charles Fine, August 2000 [19]**

Thus, the above framework proves formative in our methodology of treating the system at HIGHVOLT holistically. Leveraging these ideas, we elect to employ process flow mapping and pain point collection broadly, and in result derive supply chain architecture modifications and product modifications based upon the findings.

Fine also informs our understanding of supply chain dependency within integrally designed systems like those at HIGHVOLT and our treatment of modularity as a means for greater autonomy [19]. For example, when presented with a problematic single-source supplier issue uncovered through our research, we sought greater autonomy and control of the supply chain by moving to a more modular design (see Chapter 5). Indeed, even Fine's idea of organizational proximity informs our recommendation to consider sourcing glass fiber reinforced tubes from another Reinhausen Group subsidiary rather than continue supplying from an external source.
Chapter Conclusion

In this chapter we introduced the challenges associated with the term 'complexity' and settled upon a definition for our work. We examined the relevant work on complexity reduction and refined what we mean by 'complexity management'. We also highlighted common misconceptions like: complexity is always negative, local complexity reduction always reduces overall system complexity and the idea that complexity and modularity are always inversely related. Then, we touched on the intuitively available finding that complexity has associated costs. Lastly, we spent time elaborating on the business strategy theories which informed our methodological decisions as well as our recommendations.
4 COMPLEXITY MANAGEMENT APPROACH

This chapter will provide detailed information regarding the analytical approach of the research conducted at HIGHVOLT. Two primary techniques are employed: extensive pain-point data collection from critical stakeholders and thorough core process flow mapping. The methods are discussed in that order. Pain-point collection and analysis aim to reveal complexity in order to apply management strategies. Process flow mapping is critical to understanding where complexity enters the process, resides and is correlated to other process steps. The synthesis of process flow mapping and pain-point data illuminates challenge areas and highlights issues that, if alleviated, would better manage complexity. Classifications strategies are applied to the synthesized data to evaluate areas for action in several scopes. These classifications become even more useful when correlations are determined between the impact areas. Recommendations for complexity managing initiatives conclude this chapter.

4.1 Pain Point Collection and Analysis

To approach the problem of identifying systemic complexity drivers we surveyed experts. The individual employee doing the actual work is understood to be the subject matter expert on their part of the system. We posit that a great way to uncover complexity in the system is to ask experts what makes their job challenging, what is not going well or what they would like to change. The results of these questions amount to the pain felt by that employee, or 'pain point' and also, we suggest, directly correlate to complexity in the system. For example, if we learn in interview that employee X always has to wait for detailed engineering drawings from employee Y prior to continuing his or her work we know that this 'pain point' causes delay (and increased costs).

4.1.1 Data Collection

The first step in generating the data necessary to elucidate the complexity in the system at HIGHVOLT is selecting contributors. Significant thought is given to which core teams are necessary to survey with focus paid to known areas of delay and high-cost as well as perceived bottlenecks. Attention is also given to those with significant ability to effect the progress of a project; most notably contributors from the
engineering department. Each value-add department is surveyed to ensure completeness while supporting departments, like finance and human resources, removed from the data set. The twelve critical teams are listed in Table 1 below.

<table>
<thead>
<tr>
<th>Expert Teams</th>
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<tbody>
<tr>
<td>Operations - Logistics</td>
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<td>Operations - Warehouse</td>
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<tr>
<td>Operations - Purchasing</td>
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<tr>
<td>Operations - Order Processing</td>
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<tr>
<td>Technical - Test Floors</td>
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<td>Technical - Service</td>
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<td>Technical - Test Systems</td>
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<td>Technical - Controls</td>
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<td>Technical - Software</td>
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<tr>
<td>Technical - Transformers</td>
</tr>
<tr>
<td>Technical - Construction</td>
</tr>
<tr>
<td>Sales - Regional Managers</td>
</tr>
</tbody>
</table>

**Table 1: Twelve critical teams surveyed for pain point collection**

As noted in the cultural discussion, 'bad news' or 'complaints' are not shared in public nor in group settings. It is of critical importance that we conduct the data collection face-to-face and one-on-one to the maximum extent possible. Equally important in collecting quality data is the promise of anonymity offered to the contributors. Anonymity is agreed upon with the senior leadership and data capture and storage is isolated to the researcher's computer. Verbal interviews were the chosen method of collection because the casual, conversational tone tended to elicit more frankness and the ability to ask follow-on questions by the interviewer generated more data points. After a period of ice-breaking these meetings generally lasted much longer than planned. Buy-in from contributors and support from senior leadership for the pain point collection increased as both began to see it as a way of bettering their daily lives and the company's bottom line.

At collection, each pain point receives a classification code for tracking and for the researcher to have access to the originator (though no other person would for the reasons of anonymity stated above) for follow up as needed. Also, significant effort is given to developing the fields of information desired out of the interviews. Deliberate questions are crafted to target complexity related data generation. For example, software interfaces are queried and tracked to capture handoff and data management complexities. The researcher designed and iterated upon data collection forms in order to have uniformity and to guide inquiry towards information relevant to the
complexity discovery process. This resulted in a data collection form (see Appendix D) with such fields as: description of pain point, perceived cause, qualitative assessment of ease or difficulty to alleviate, suggested remedies, software factors including future needs, interfaces with other departments or divisions, problem component/accessories-functional group, etc. During interviews answers were handwritten on the data collection form or typed into the form digitally.

Several interview sessions are performed with each of the twelve critical teams. The teams also have access to the researcher to add new pain points or discuss remedies. Follow-ups are performed with each team after the pain points are digitized for verification that the contributor’s pain point is properly captured and to allow the opportunity to add additional information.

In total, 155 pain points were collected from the 12 teams. On average each team contributed 12 (mode of 11). The maximum from one team was 21, the minimum was 5. We find the large number of data points reflective of the confidence into the method by the twelve teams surveyed. Significant relationships between the pain points are also indicated and will be elaborated upon in Section 4.3. Only four of the pain points collected were considered unusable due to their personal complaint nature. One hundred fifty-one pain points are used in the follow-on analysis.

4.2 Core Process Flow Mapping

A core process flow map historically did not exist at HIGHVOLT prior to this project, as the process landscape was developed in an evolutionary process. To develop a deep understanding of the business mechanics and to generate a landscape upon which to evaluate complexity entering, residing and moving throughout the system the core processes are mapped and validated.

4.2.1 Mapping the As-Is Process

Before attempts at managing complexity are made, full understanding of the current state process is critical. To facilitate the collection of this knowledge existing company documents are used to classify core activities. Every activity is described in a standardized format and captured on a data collection sheet (see Appendix E). This activity description form includes the following data fields: activity name, activity ID, recurrence, duration estimate, man-hour estimate, cost estimate, inputs, outputs,
responsible parties, activity description, templates, procedures, supporting
documents and lessons learned. Each activity critical to the core process value stream
is decomposed following this format from existing company documents. Mapping the
as-is process flow is completed by linking the activities with their appropriate
interfaces to other activities.

The resulting as-is core process flow map serves as our foundational landscape upon
which to understand and evaluate the effects of complexity in the system. An excerpt
from the full current state process flow map is provided in Figure 10. Importantly, it
should be noted that this core process flow map is the idealized process generated
from company documents and directives. Next, the as-is process flow map is
challenged and assessed for accuracy.

![Figure 10: Excerpt of the process flow map](image-url)
4.2.2 Validation of the As-Is Process Flow Map

Process flow maps are of limited utility if they do not accurately reflect what is actually occurring along the value stream. Therefore, validation of the as-is process flow map is necessary. Interviews with subject matter experts from the critical teams are conducted to assess the accuracy of the as-is process flow map and make the necessary changes or additions. Again, anonymity is important as employees do not want to be identifiable as not adhering to company directives. Only minor changes were required to more accurately reflect how the process truly works at HIGHVOLT.

4.2.3 Initial Findings

Because of the customized, project nature of HIGHVOLT’s business a standardized process flow is challenging to generate. Often the experts expressed discontent at needing a map; believing it would lead to more rigidity in a system in which they enjoy working through their informal networks and communication channels. This feature again highlights the cultural implications of highly skilled employees who take pride in just ‘making it happen’ when needed. This reliance on informal pathways and power structures permeates the company. Self-organized informal communication and information flows are very challenging to capture and highly influential on how the value stream progresses. (In fact, the process flow was designed in 1993 when the company had approximately 60 employees [20].) As these informal interfaces developed when HIGHVOLT was a significantly smaller company, they did not scale well. Speaking of these informal interfaces and their effect on the process flow, one senior employee noted, “The company lives on the capability of the OPS [operations] team to intrinsically compensate for the communication shortcomings” [21]. In repeated projects (of which there are few) self-organization lends to each person doing their part and the process flow works well, yet when new interfaces have to be served the process breaks down. These missed handoffs and lacking interfaces leave room for inefficiency and complexity to creep into the process. In the results section, we present a fully synthesized discussion including results and recommendations taking into account these informal interfaces.

The next main finding from the generation of the core process flow map is the recognition that much of the complexity and variance in the flow are introduced by external actors. As noted previously, the market and customers HIGHVOLT serves
exert a great deal of influence outside the control of the enterprise. Customers exist outside of direct control of HIGHVOLT and appear to drive significant amount of process rework loops and communication flows which are not depicted on the generalized process flow map. The other external actor with strong influence is the independent supplier. Understanding the complexity induced by these external actors gives the opportunity to attempt management strategies. Further discussion regarding these types of complexity drivers is found in Section 4.3 where we synthesize the pain points and process flow. A case study in Chapter 5 provides a formalized example of a managing strategy applied to an external actor—a high-voltage capacitor supplier.

4.3 Synthesis of Pain Points and Process Flow

We use the process flow landscape as a platform upon which to chart the pain point data in order to increase clarity and reveal trends. The synthesis of process flow mapping and pain-point data illuminates challenge areas and highlights issues that, if alleviated, would result in more managed complexity. The impact areas discovered provide ways to 'tackle' complexity; for example, they are projects that if undertaken would alleviate the pain points associated with the impact area. Specific 'problem' components or subsystems are also revealed employing these techniques.

4.3.1 Mapping Pain Points to the Process Map

The validated process flow map is used as a platform to examine the pain points. We begin by physically charting the pain points (by code) to a position on the process flow map. Nearly all of the pain points can be placed near an activity or group of activities, providing a way of conceptualizing where the pain point resides, which signifies where complexity resides. Through the exercise of overlaying the pain points onto the process flow map interesting findings emerge. Repetition, clustering, large impact areas and cause-victim relationships become visible as the pain points are charted.

Repetition signifies that some pain points were expressed by multiple reporting teams. When several teams report the same or similar issue relative importance as well as scope of impact can be inferred. On the first iteration of the exercise every pain point was charted, in subsequent analysis repeated occurrences of the same issue are grouped.
Clustering is when several pain points reside in an area of the process flow map. Many pain points clustered at one activity on the map suggest it an area warranting further investigation. The degree of similarity or difference of the pain point topics clustered together also provides insight into issues which may be related. Cluster areas analyzed with their group of pain points yields information about interface mechanisms which are working or failing at those locations along the process flow map. Figure 11 below depicts a cluster area about the activity 2.4.1.1 Purchase Parts. Interestingly, the clustered pain points originate from 3 different teams.

![Figure 11: Example of clustering of pain points](image)

Large impact areas are where a pain point or group of pain points have effects upon a large area of the process flow map rather than just one activity. These large impact areas suggest a degree of severity of the pain point or magnitude of the effect caused on the overall system by those pain points which have a broad impact. Pain points with large impact areas also represent the opportunity to manage the complexity of a large area of the process by alleviating that single pain point. For example, in Figure 12, the pain points listed to the right of the activity boxes 2.2.3.2, 2.2.3.3, and 2.2.3.4 effect all of those activities. This represents large-impact area pain points.
Associations between process activities are revealed by charting where a pain point is 'caused' or originates and where such 'pain' is 'felt'. We term these cause-victim relationships. Tracing back from where the pain point is felt to where it is caused provides information on how to mitigate that pain point or improve the relationship. Sometimes revealed cause-victim relationships are clearly examples of failed interfaces or lacking information channels. Other times, the cause-victim relationship originates from outside the enterprise (from customers or suppliers) but can still be evaluated for mitigation strategies. Below, in Figure 13, cause-victim examples are shown highlighted in green. For example, pain point TF8 is caused by 2.2.1.3, Order Modification, and experienced by 2.2.3.2, 2.2.3.3, 2.2.3.4.
The process of building the pain point data onto the process flow map also necessitated deep analysis and discussion about each pain point, the likely cause, its results and gave the chance to postulate about what might alleviate it. Additionally, this exercise revealed commonalities and associations between the pain points allowing the researcher to develop a classification strategy. Seeing the pain points where they reside and how they are connected provided the opportunity to observe natural groupings; for example, similar causal factors, missing processes or lacking interfaces.

4.3.2 Type Classification of Pain Points

The first classification scheme is type classification (the second method is impact area classification and follows in section 4.3.3). Here each pain point is classified into one of four type categories: SAP transition related issue (necessary for a parallel project ongoing at HIGHVOLT), product or portfolio issue, process issue and cultural or leadership issue. This method is helpful because it gives clarity to immediately actionable items. Also, an indication of the relative preponderance of the types of
complexity is revealed. Though none should be eliminated from attempts to manage complexity, as data show, relatively few of the pain points (complexity drivers) are product or portfolio related. The full numerical break down from this type classification scheme is seen in Table 2.

<table>
<thead>
<tr>
<th>Type Classification</th>
<th>Number of Pain Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: SAP/M5</td>
<td>54</td>
</tr>
<tr>
<td>2: Product/Portfolio</td>
<td>13</td>
</tr>
<tr>
<td>3: Process</td>
<td>59</td>
</tr>
<tr>
<td>4: Culture and/or Leadership</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>155</td>
</tr>
</tbody>
</table>

Table 2: Type classification of pain point data

As seen in Table 2, 54 of the pain points collected are classified as an SAP-migration issue. This is of immediate strategic importance to the leadership of HIGHVOLT. As a result of this methodology no time was lost in providing the team responsible for the migration data to help them avoid rework or mistakes in the architecture of the new SAP system. Fifty-nine of the pain points are classified as process related. This strongly justifies further inspection of the pain point to process flow mapping and guides the second classification method described in Section 4.3.3. Twenty-nine of the pain points are classified as a cultural or leadership challenge. These are inherently long term projects. The use of this classification method clearly grouped the learning points, allowing recommendations to be made to senior leadership.

Additionally, the type classification method helps facilitate a temporal analysis. Management can be informed rapidly to issues in need of immediate action and those that will either take time or can simply wait. Figure 14 below reveals a breakdown possible through the type classification process. We found ten immediately actionable, 'quick wins' while doing the type classification and leadership were able to act on them right away. Also of note are five issues which stood out from the data as issues requiring strategic reflection and decision on executive leadership.
4.3.3 Impact Area Classification Method

The second classification method involves using process flow-to-pain point mapping which enables the researcher to determine natural groupings. We will call these natural groups 'impact areas'. This scheme further analyzes the data to discover similarities between pain points; for example, similar causal factors, individual actors, interfaces, cultural challenge, etc. The pain points are grouped logically while retaining the positional information gained by charting them upon the process flow map. Effectively, these impact areas represent challenge areas or projects, that if undertaken, would alleviate the pain points in that group. The project thereby managing the complexity related to those challenge areas. These underlying groupings become apparent upon thorough inspection of the overlaid pain point to process flow data. One hundred fifty-one of the one hundred fifty-five (97.4%) pain points were classifiable into one of these impact areas. The thirteen impact areas are found below in Table 3.

<table>
<thead>
<tr>
<th>Thirteen Impact Area Classifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Management</td>
</tr>
<tr>
<td>Legal Framework</td>
</tr>
<tr>
<td>Defining Responsibility</td>
</tr>
<tr>
<td>Specification Clarification</td>
</tr>
<tr>
<td>Tool Needed</td>
</tr>
</tbody>
</table>

Table 3: Thirteen impact area classifications

On inspection, each of these impact areas are actionable at different levels in the organization. Properly assigning an impact area where it can best be addressed lends
simplicity and allows faster action. Undertaking projects on the proper level within the organization is enabled through this process. Figure 15 defines the levels within HIGHVOLT the impact areas are assigned to.

Next, each pain point is assigned to a primary impact area. The classification is a qualitative decision by the researcher made with the assistance of subject experts based upon what is believed to be the primary causal area of the pain point. This classification step illuminates the largest impact areas by number of pain points. This, in turn, guides discussion on the prioritization of impact areas for further inspection and action. Then, all of the pain points are assigned to a secondary impact area. This step reveals connections between pain points; in effect, drawing out the interfaces between the impact areas. As we will show, high correlation is evident between certain impact areas. This finding serves as an excellent guide to qualify which impact areas will reap the highest pay-off when projects are undertaken in conjunction.

4.3.4 Results of Impact Areas Analysis

Each of the thirteen impact areas are evaluated in several ways. First, we assess how many of the 12 teams of subject matter experts reported a pain point falling into that impact area. For example, from Table 4 below, eight of the teams reported one or more pain points classified as a 'defining responsibility' issue and 12 of 12 teams reported one or more pain points in the 'project management' and 'legal framework' impact areas. The number of teams reporting an issue in a specific impact area suggests the pervasiveness and / or scope of an issue. This can also be considered a relative measure of the amount of complexity induced by the issue. Next, the impact
areas are evaluated for number of pain points classified in the category as a Primary Impact Area (PIA), and how many as Secondary Impact Area (SIA). As an example, while only 11 pain points are classified with Primary Impact Area 'project management,' 38 pain points have a Secondary Impact Area classification of 'project management'. Lastly, impact area totals, either PIA or SIA are summed to reveal relative dominance of some impact areas. Using the example above, one can see that 49 pain points have a classification of 'project management' impact area (either PIA or SIA).

<table>
<thead>
<tr>
<th>Impact Area</th>
<th>Number of Different Teams Reporting</th>
<th>Primary Impact Area (PIA)</th>
<th>Secondary Impact Area (SIA)</th>
<th>Total PPs with PIA/SIA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Management</td>
<td>12</td>
<td>11</td>
<td>38</td>
<td>49</td>
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<tr>
<td>Legal Framework</td>
<td>12</td>
<td>27</td>
<td>3</td>
<td>30</td>
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<td>Timeline Management</td>
<td>11</td>
<td>22</td>
<td>14</td>
<td>36</td>
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<tr>
<td>Define Responsibilities</td>
<td>8</td>
<td>21</td>
<td>4</td>
<td>25</td>
</tr>
<tr>
<td>Head ROM</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Specification Clarification</td>
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<td>11</td>
<td>2</td>
<td>13</td>
</tr>
<tr>
<td>Contingency Management</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>DFMA Acceptance</td>
<td>7</td>
<td>10</td>
<td>9</td>
<td>19</td>
</tr>
<tr>
<td>Manning/HR</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>One Piece Flow</td>
<td>2</td>
<td>3</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Stan &amp; Mod</td>
<td>6</td>
<td>4</td>
<td>10</td>
<td>14</td>
</tr>
<tr>
<td>Info Management</td>
<td>9</td>
<td>12</td>
<td>18</td>
<td>30</td>
</tr>
<tr>
<td>Tool Needed</td>
<td>7</td>
<td>14</td>
<td>7</td>
<td>21</td>
</tr>
</tbody>
</table>

Table 4: Impact area analysis reflecting number of teams reporting, primary and secondary impact area classifications

By assigning a Primary Impact Area classification and a Secondary Impact Area to each pain point we are able to create a correlation matrix. This provides valuable information to decision makers about what areas may have positive overlap effect and which projects will have synergistic effects when undertaken in coordination. Table 5 displays this matrix of correlation. For example, ten pain points with 'legal framework' PIA have 'project management' as their SIA classification. This information is utilized to conceptualize how to maximize the degree of complexity management in the most efficient way possible. This method is manageable due to the relatively small number of categorizations; in a case where there are more classification areas a design structure matrix (DSM) method can be used. A top-level, basic DSM approach applied to this data set fails to partition the data in a meaningful
way due to the significant, pervasive overlap, however, the basic matrix is provided in Appendix F for review [22].

Utilizing Table 5 to visualize weighted overlap significance, the researcher makes recommendations based upon the most numerous, pervasive, positively correlated and most likely to reap high reward for undertaking projects applying treatment to the impact areas.

<table>
<thead>
<tr>
<th>Primary Impact Areas (PIA)</th>
<th>Secondary Impact Areas (SIA)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Project Management</strong></td>
<td>Legal Framework</td>
</tr>
<tr>
<td></td>
<td>Timeline Management</td>
</tr>
<tr>
<td></td>
<td>Lacking Defined Responsibilities</td>
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<tr>
<td></td>
<td>Head BOM</td>
</tr>
<tr>
<td></td>
<td><strong>Specification Clarification</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Contingency Management</strong></td>
</tr>
<tr>
<td></td>
<td>DFMA Acceptance</td>
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<tr>
<td></td>
<td>Manning/HR</td>
</tr>
<tr>
<td></td>
<td>One Piece Flow</td>
</tr>
<tr>
<td></td>
<td>Standardization and Modularization</td>
</tr>
<tr>
<td></td>
<td>Info Management</td>
</tr>
<tr>
<td></td>
<td><strong>Tool Needed</strong></td>
</tr>
</tbody>
</table>

Table 5: Correlations matrix displaying interactions between impact areas

Three dominating impact areas are visible in the data. Project management, legal framework and timeline management represent the largest impact areas by number of pain points associated, the number of teams reporting and the positive correlations to one another. Figure 16, displays the relationship of these impact areas which we will now call the High Impact Areas (HIA). The High Impact Areas represent the largest pay-off complexity management projects that HIGHVOLT can undertake. Addressing these impact areas will dramatically alleviate the pain points expressed.

Figure 16: High Impact Areas. Number of pain points and correlations between PIAs and SIAs
Still greater positive effects can be achieved by adding two additional impact areas to an action plan. We will call these Enabling Impact Areas (EIA). They are 'specification clarification' and 'defining responsibility'. Figure 17 adds the two enabling impact areas graphically to depict the additional pain point alleviation and positive correlation to the High Impact Areas.

The five impact areas depicted above represent the best solution for managing complexity in the system given limited time and budgetary constraints. While all the impact areas deserve attention, the methodology applied allows for prioritization. Also of interest, DSM methods are applied to the normalized data found in Table 5 to reveal helpful associations to inform project team selection and tasking. Figure 18 provides a partitioned DSM from the impact area classification relationships (any normalized relational value below 0.1 removed). This figure demonstrates which impact areas should be addressed with coordination and affords decision makers the ability to task teams with complementary work. For example, 'standardization and modularization' should be undertaken with 'DFMA acceptance' measures.
The full recommendations found from the results of this analysis approach to complexity management are found in Section 6.1.

4.3.5 Reflections on Organizational Complexity

Organizational complexity issues are apparent throughout the data. This project merely skims the surface of organizational complexity in such a way as to address areas illuminated by the pain point to process flow mapping synthesis. For the most part, issues regarding formal structure or internal politics are noted and passed to executive leadership for their awareness. Little can be addressed in this arena by the researcher. Other findings regarding cultural norms are addressed in the recommendations found in Section 6.1. Future work, Section 6.3, addresses some interesting follow-on work possible from this data, particularly more in-depth use of DSM and MDM as well as application of complexity metrics.
5 CASE STUDY: SINGLE SOURCE SUPPLY OF HIGH-VOLTAGE CAPACITORS

The process of discovery, correlation and analysis not only afforded High Impact Areas for targeted improvement projects and also brought to light specific complexity-driving components or subsystems. This chapter presents a case study in alleviating a large complexity and risk driver discovered within the system.

Here we present an investigation of methods to alleviate this single source supply issue. First, a discussion of the supply issue and its complexity factors is introduced. Next, a technical overview of alternating current (AC) high-voltage (HV) capacitors is provided with structural and functional decompositions. A new modularized portfolio solution is presented along with the researcher’s development process to arrive at the new technical solution. Lastly, business ramifications and implementation recommendations are discussed.

To summarize, a new technical solution is optimized through increased modularization to reduce variants in the product portfolio while maintaining essential flexibility. The resulting solution affords the opportunity to negotiate with new potential suppliers, increasing the supplier base, and improves HIGHVOLT’s bargaining position with the existing supplier; thus decreasing overall risk. Additionally, an overall decrease in delivery time is afforded due to reducing the effects of high-voltage capacitor delays on the critical path of production in a majority of orders.

5.1 Current Single-Source Supplier Issue

The methodology employed to illuminate complexity drivers reveals serious delay and high cost associated with capacitor sourcing at HIGHVOLT. Many of the surveyed teams express concern about the delay and re-work caused by dealings with the single supplier of these capacitors. Those with access to sourcing cost information also report exceedingly high costs associated with the capacitors. Understandably, considering HIGHVOLT’s product offerings and project business model, highly unique capacitors are requested of the supplier in very small quantities—most often order sizes of one. The supplier exerts significant power over the entire process flow of a
project at HIGHVOLT simply based on when the capacitor is actually delivered. Currently, the supplier has little motivation to make promised delivery timelines and delivery dates are often 14-18 weeks from order placement.

Interestingly, it is process complexity analysis that leads the researcher to the discovery of this issue, which is both process and product complexity related. The importance of this cannot be understated as it justifies a more holistic look at complexity at large to determine areas to target for management. The main objective in targeting the single source supply issue is truly managing the whole-system risk and complexity it causes. Cost savings and delivery time improvement are secondary objectives. Better positioning for HIGHVOLT in the supply chain is paramount regarding this issue.

First, the current state of capacitor sourcing is explored. We find that over 580 live unique AC capacitors are currently in the ERP data, going back approximately 6 years. There is a disconnect worthy of note in the data. We have data on what was ordered from the supplier in the last 6 years; however, we are unable to link this data specifically with what was requested by the customer. Essentially, it is unclear how / if the ordered units were configured in series and / or parallel to meet the system requirements after delivery at HIGHVOLT to suit a customer's specific need. Simply put, we know via separate systems what was ordered, and what was requested by the customer and yet nothing about how what was ordered was combined (if at all) to meet customer needs. This data-gap is provided for transparency as we believe use of the ERP data provides sufficient framework through which to analyze the current sourcing methodology. The ERP data is used as a guide for what has historically been ordered to meet functionality requirements of the test suites.

Also of note, some time ago, a preferred capacitor list was generated between the technical experts of HIGHVOLT and the supplier. However, this list is not generally accepted by the system designers at HIGHVOLT as evidenced by the ERP data showing over 580 live capacitors. Significant exploration as to why this is the practice was necessary to determine the path ahead.
In assessing the importance of this component on overall critical path production of orders a theoretical Gantt chart is helpful. Each project Gantt chart at HIGHVOLT is highly individual, however, experts claim the majority of projects are delayed by the current high-voltage capacitor sourcing. If we can reduce overall time to delivery of a test system, significant savings are ensured. Figure 19 depicts this generalized process flow with $L$ being the overall time spent in in-house manufacturing stage prior to system assembly. The variable $c$ represents the duration of time required to receive a custom high-voltage capacitor. In cases where $c$ is greater than $L$ the critical path is delayed by the single component. With high level of confidence, the order processing experts at HIGHVOLT note that this particular component is a regular constraint on the overall production process operating with in-house manufacturing length $L$.

![Diagram of Gantt chart](image)

*Figure 19: Theoretical Gantt chart demonstrating critical path time determination*

### 5.2 Technical Overview of Alternating Current (AC) High-Voltage (HV) Capacitors

Top-level structural and functional analyses are conducted to establish necessary foundational knowledge. The information generated serves as a check for the researcher, insuring required functions and structural needs are preserved in the development of the new technical solution. Many of the internal technologies are trade secrets for the few high-voltage capacitor manufacturers and thus closely held. While the basic function of a capacitor is simple, requiring just a dielectric and two electrodes, high-voltage capacitor manufacturers maintain their competitive advantage by preserving secrecy regarding their in-house optimized designs [23]. However, the critical elements for grasping the proposed new technical solution are accessible and explained below.
5.2.1 Structural Analysis and Decomposition

For technical context, we perform a structural analysis and decomposition of the AC HV capacitors of interest in this case study. The general design of the HV AC capacitor includes the capacitive assembly, insulator, connectors and base. The capacitive assembly is further decomposed into capacitive devices, protection devices, and connections between capacitive packages. The insulator decomposes to: glass fiber reinforced polymer tube (GFRP), bottom lid, top lid and screen electrodes. There are two connectors, top and bottom. The base generally includes just a support structure, and can be modified based on customer requests to include transportation devices and / or metering devices. Figure 20 displays an example multi-capacitor system configuration while Figure 21 graphically shows the structural decomposition findings.

Figure 20: High-voltage AC capacitor used as a voltage divider (right), HV filter, and coupling capacitor [24]
Structural Decomposition

AC High-Voltage Capacitor

- Insulator
  - GFRP Tube
  - Bottom Lid
  - Top Lid
  - Screen Electrode(s)

- Capacitive Assembly
  - Capacitive Devices
  - Protection Devices
  - Connections Between Packages
    - Grading Resistors
    - Fuses
      - Dielectric

- Connectors
  - Top Connector
  - Bottom Connector

- Base
  - Support Structure
  - Transportation Device
  - Metering Device

--- Optional Component

Figure 21: Structural decomposition of AC HV capacitors
5.2.2 Functional Analysis and Decomposition

We conduct a functional analysis with HIGHVOLT's current AC capacitor portfolio for two reasons. First, a deep understanding of the functions of the capacitor in the complete test systems is necessary prior to undertaking a complexity management endeavor. Secondly, we must insure we retain all necessary functions of the capacitors currently in use so as not to weaken the flexibility of the overall systems offered by HIGHVOLT. In this case study, we aim for essential complexity, which is “the minimum amount of complexity, which is necessary to deliver the required function [15]” and remain competitive in the market.

HIGHVOLT offers a wide range of capacitances and voltages to meet test system needs. They are used for:

- the high-volt arm of capacitive voltage dividers
- coupling capacitors and high-voltage filters in partial discharge measuring circuits
- basic load capacitors in resonant circuits to enable the alternating current high-voltage generation in the no-load case of the system [24]

Also of note, sometimes all of the above functions can be accomplished by one specialized capacitor, sometimes multiple are required [24]. Figure 22 below provides a functional overview of the three types of AC capacitors used in this case study.
Capacitors in use in HIGHVOLT test systems must achieve four primary functions: deliver capacitance while meeting performance requirements, withstand ageing, meet safety requirements and provide dielectric insulation to the test system. Each of these primary functions are further broken down. To deliver capacitance the unit must supply stable voltage, deliver current, and meet charging and discharging time requirements. Withstanding ageing requires specific material selections, design parameters and manufacturing choices. In order to meet safety requirements both design and manufacturing choices are uniquely made. Lastly, design choices are pivotal in achieving the function of providing dielectric insulation to the system. Figure 23 depicts these elements of decomposition as well an additional layer deeper in necessary areas.

Understanding the critical functions of the AC HV capacitors allows the researcher to pursue complexity management strategies while preserving effective function. With the structural and functional requirements known, we proceed in generating a new technical solution.
Functional Decomposition

High-Voltage Capacitor

Deliver Capacitance While Meeting Performance Req's
- Supply Stable Voltage
- Deliver Current
- Chemical Properties
- Electrode Properties
- Dielectric Properties
- Meet Charging/Discharging Time Req's

Withstand Ageding
- Material Selection
- Uniformity of Surfaces
- Cross Section of Current Carrying Component
- Wettability
- Matrix Design Serial/Parallel
- Thinness of Layers in Capacitive Elements
- Edge Phenomenon Consideration
- Material Choices
- Design Parameters
- Design

Meet Safety Req's (Structural Integrity)
- Manufacturing Choices
- Design
- Manufacturing Choices

Provide Dielectric Insulation in the Test System
- Design Choices
  - Height Selection
  - Glue Selection
  - Test Voltage Distribution
  - Connection Technology - GFRP Electrode
  - Overpressure Relief System Design
5.3 New Modularized Technical Solution

From discoveries made through the structural and functional analyses the researcher determines that sourcing capacitance instead of individual capacitors may be possible and could allow for an increase in order size and a streamlined portfolio. Both of these possibilities would have a positive effect on the complexity generated by the single-source issue with the AC HV capacitors.

5.3.1 Goals of the New Solution

While modularization strategies are most often associated with improving cost per unit the researcher determined that employing a modularization and variant reduction strategy can retain the functions of the capacitor in the high-voltage test systems while reducing the complexity and risk associated and improving the supply chain dynamics. The researcher aims to find a solution that can be ordered via forecasts in order to reduce delivery time and burden upon the supplier allowing for stronger negotiating power and the potential to source from a secondary supplier, if needed. A secondary benefit, if attainable, would be cost reduction in the sourced capacitor. In all, the new technical solution should: a) meet functional requirements for HIGHVOLT’s test suites, b) allow for shorter delivery times and, ideally, c) reduce purchase price.

5.3.2 Development Method of the New Solution

To develop new potential technical solutions two independent paths are taken. Each path involves different starting assumptions. At the end of each deep investigation the two paths converge upon a similar solution. We will discuss each path to solution independently and then synthesize the results in discussion of the optimized solution.

Path 1:

Baseline assumptions for the first path center around a previously generated ‘preferred capacitor’ list agreed upon by HIGHVOLT and the supplier’s engineers (Table 6 displays preferred combinations in bold). This list comprises the supplier’s wishes, though in practice, it was not being followed as is evidenced by the number of individual active capacitors in the ERP system. It appears, on inspection, that HIGHVOLT’s engineers are designing new capacitors frequently and deviating from...
the 'preferred capacitor' list more than adhering to it. In fact, another document available to customers and used in-house includes 92 variants of AC HV capacitors [25]. Acknowledging that the supplier generated the capacitance and voltage combinations on the preferred list we make the assumption that the supplier would prefer to produce the new solution in these capacitive and voltage measures.

<table>
<thead>
<tr>
<th>Rated voltage in kV</th>
<th>50</th>
<th>100</th>
<th>160</th>
<th>200</th>
<th>250</th>
<th>300</th>
<th>350</th>
<th>400</th>
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<td>0.5</td>
<td>0.4</td>
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</tr>
<tr>
<td>H</td>
<td>25</td>
<td>16.7</td>
<td>12.5</td>
<td>10</td>
<td>8.33</td>
<td>7.14</td>
<td>6.25</td>
<td>5</td>
<td>4.18</td>
<td>3.57</td>
<td>3.12</td>
<td>2.5</td>
<td>2.08</td>
<td></td>
</tr>
</tbody>
</table>

Table 6: Rated voltages and capacitances (types in bold letters are preferred) [24]

Various other assumptions are necessary to develop a proposed new solution. These assumptions are made with the consultation of expert design engineers at HIGHVOLT and the sourcing expert. Utilizing both areas of expertise, decisions are made for technological limitation, logistic, mechanical and cost reasons. The other fundamental assumptions and justifications are listed below in Table 7.

<table>
<thead>
<tr>
<th>Path 1 Assumptions</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 50 kV capacitors will be eliminated from consideration</td>
<td>50kV systems are available from many suppliers, thus not subject to single-source issue</td>
</tr>
<tr>
<td>2 Symmetry of modules does not matter</td>
<td>Technical functions do not depend on symmetry. Considerations for connectors remain important</td>
</tr>
<tr>
<td>3 500kV module is not available from the supplier</td>
<td>Currently supplier will not provide a single stand-alone 500kV</td>
</tr>
<tr>
<td>4 Maximum 3 modules in series to 1200kV (to make a capacitive column)</td>
<td>Cost decision for the number of connection points and screening electrodes required if more are allowed in series</td>
</tr>
<tr>
<td>5 Maximum 4 modules for 1600kV unit</td>
<td>Demonstrative that growth into high kV regions possible</td>
</tr>
<tr>
<td>6 Maximum 4 capacitive columns in parallel</td>
<td>Logistic and space constraint</td>
</tr>
<tr>
<td>7 Only like capacitance columns can be combined in parallel</td>
<td>Technological limitation</td>
</tr>
<tr>
<td>8 Preference given to using as few modules as possible to make a column</td>
<td>Cost reduction constraint</td>
</tr>
<tr>
<td>9 Preference given to using as few columns as possible to make a system capacitor</td>
<td>Cost reduction constraint</td>
</tr>
</tbody>
</table>
Additionally, the decision is made to have only 100kV steps in voltage size after confirmation from the design teams that 100kV increments will meet the functional requirements of the test systems.

After exploring the combinations available, adhering to the above assumptions we elect to use nine capacitance modules as seen in Table 8. These values are the 100kV, 300kV and 400kV 'preferred capacitance' values as seen in Table 6 in bold.

<table>
<thead>
<tr>
<th>Rated kV</th>
<th>0.1</th>
<th>0.3</th>
<th>1</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 kV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300 kV</td>
<td>0.33</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>400 kV</td>
<td>0.25</td>
<td>2.5</td>
<td>6.25</td>
<td></td>
</tr>
</tbody>
</table>

Table 8: Available capacitive modules path 1

Combining the above capacitance modules in series affords a broad portfolio of capacitor columns. The available capacitive columns are shown in Table 9 below. The 1600kV is depicted in red because its experimental nature would require extensive testing by the engineering department prior to its deployment with a test system. As an example of how to read this table, we will use the 200kV systems below which the (100+100) demonstrates this column will be made with two, 100kV modules. Above each capacitance value for the 200kV line one can see the capacitance value of the module, for example, 0.1 signifies that two 100kV units with 0.1 capacitive values are connected in series to provide a column with parameters of 200kV and 0.05nF capacitance. The line with 0.1 and 0.3 signifies that one 100kV, 0.1nF unit and one 100kV, 0.3nF unit combined in series provides a system capacitance of 0.075nF. These values reflect the results using the formula for total capacitance connected in series:

\[
\text{Series Capacitances} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \ldots + \frac{1}{C_n}}
\]

While the total value of the kV is summed when connected in series.
Table 9: Path 1 portfolio options with system voltage and total capacitance

Table 9 shows that from the 9 modules, 36 unique and currently useful capacitive columns can be made using just series connections (excludes those for 1600kV due to experimental nature).

To further expand the portfolio using only the 9 modules, capacitive columns are combined in parallel. Combining capacitors in parallel yields the following capacitance:

\[ C_{\text{total}} = C_1 + C_2 + \ldots + C_n \]
Eighty useful capacitors are available using the 9 preferred modules combined in series and parallel with up to three columns combined in parallel (as shown in Table 10). Useful capacitance values are defined as capacitance values at or above 0.050nF. This value is determined by the ABAS order information and interviews with the technical experts.

This modularization method using capacitive modules in series and parallel brings the unique modules to 9 while maintaining 80 useful combinations. These 80 available combinations cover the spectrum of necessary variants per the design engineers at HIGHVOLT.

A reduction to 9 modules from over 580 unique live capacitors is, indeed, a drastic reduction in portfolio complexity. Of course, assembly and testing of the series and parallel combinations must be accomplished and will add workload. A full discussion of the ramifications of the modularization strategy are found in Section 5.4.

Path 2:

When seeking validation of the proposed solution from path 1 with a technical expert¹ at HIGHVOLT a new path is proposed. This path includes some of the assumptions

¹ Enrico Bilinski, transformer and systems designer at HIGHVOLT, developed the path 2 findings by building upon the work done on path 1. He significantly contributed to the final optimized solution.
from path 1, and deviates in some important ways. Rather than repeating the similar assumptions, Table 11 instead depicts where path 2’s assumptions deviate from those of path 1. Importantly, the key differing assumption is listed as number 1. Path 2 does not assume the previously pursued ‘preferred’ modules should be used as the foundational building block for the complexity reducing modularization strategy.

<table>
<thead>
<tr>
<th>Path 2 Assumptions (That differ from Path 1)</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Does not assume &quot;preferred&quot; capacitance values as a starting point for selection of modules.</td>
<td>Argument that there is no evidence supplier would still prefer these modules with a new modularized strategy. Requires coordination with supplier to know feasibility.</td>
</tr>
<tr>
<td>2. Remove from module portfolio any unit less than 1nF</td>
<td>Technical decision as 1nF modules can be combined to meet the functions of anything needed by the customers.</td>
</tr>
<tr>
<td>3. Use same core packets to build columns from 100kV, i.e. 200kV columns are two 100kV modules of the same capacitance inside.</td>
<td>Mixing capacitance values to make the same column is feasible, but not necessary to meet functional demands.</td>
</tr>
<tr>
<td>4. Symmetry of modules is used in accordance with reactor design.</td>
<td>Limits the kV values possible with module combinations but engineering claims it will not effect the ability to service current test systems portfolio.</td>
</tr>
</tbody>
</table>

**Table 11: Path 2 assumptions that differ from path 1**

From these assumptions, Table 12 shows the chosen modules.

**Table 12: Available capacitive modules path 2**

Next, combinations of like capacitive value modules are combined in series to provide the columns in Table 13. Notice where total capacitive values would be below 0.17nF when connected in series no value is given. This reflects the lack of need for capacitors of these parameters.

**Table 13: HVAC capacitors with series connections up to three capacitors**

Path 2 also connects the capacitive columns in parallel to expand the portfolio to higher capacitive values. Connecting two like columns in parallel yields the added Table 14 portfolio choices (remembering that capacitance is additive while nominal voltage will remain the same).
Table 14: Portfolio additions using two like modules in parallel connection

Connecting three like columns in parallel yields the additional Table 15 portfolio choices.

Table 15: Portfolio additions using three like modules in parallel connection

Path 2 provides 52 types of different AC HV capacitors from 5 types of capacitor modules.

5.3.3 Optimized New Technical Solution

Path 1 and path 2 provide two viable technical solutions given some different starting assumptions. These assumptions are made based on hypotheses about what the supplier would be most willing to agree to produce. That said, without pursuing technical conversations with the supplier we cannot be sure which path is preferred. Having two proposed solutions certainly increases the flexibility and negotiating potential with the supplier.

Before recommending entering into discussions with the supplier the researcher elects to optimize a solution from the findings in path 1 and path 2 so as to present the most favorable suggestion to HIGHVOLT. During the discovery process we find the importance of minimizing not only the number of capacitive packages but also the
variance of diameter and length of insulator tubes (GFRP). Path 2 method requires just 4 different lengths and 4 different diameters of insulator tubes (GFRP) which addresses the additional bottleneck found in the system: the delay and lead time of acquiring the GFRP tubes from suppliers.

Combining the foundational ideas from path 1 (minimizing variance through modularization via capacitive modules and then combining the modules with series and parallel to meet the needs of the specialized test systems) and the minimizing of diameters and length of GRFP tubes from path 2 we settle upon a best solution. We recommend the basic portfolio of different capacitors from 5 modules available from path 2 (see Tables 13, 14, 15 for review) with the addition of a 1000kV model created by removing the 900kV options and allowing for asymmetric combination of packages using 2x 400kV + 1x 200 or 2x 300kV + 1x400kV. System requirements necessitate a 1000kV capacitor which is not currently available via path 2.

### 5.4 Business Ramifications

The new optimized technical solution provides several improvements to minimize complexity at HIGHVOLT. First, by ordering capacitance instead of capacitors from the supplier forecasting on an annual or quarterly basis can be achieved. This benefits the supplier as they are no longer receiving orders with a lot size of one for a very specialized capacitor. Meaning that HIGHVOLT will experience significantly less delivery delays and potentially even lower prices per capacitor. Arguably, this method of sourcing capacitance also introduces the option of seeking several other capacitor manufacturers for qualification. The threat of pursuing other suppliers with this newly simplified portfolio may be enough to influence cooperation by the current supplier.

Importantly, the new technical solution does move some complexity from the supplier to in-house construction of the capacitors from the modules. This effectually increases complexity at a specific position in the process flow. Where this complexity is induced is an area which has capacity to handle it. Also, with the variance moved in-house it is much more transparent and easier to influence. This is a hallmark example of the benefits of managing complexity rather than simply trying to reduce it. Moving complexity to a place in one’s system where it can be handled to benefit the overall process flow can yield many positives to overall system complexity.
The implementation plan will require getting supplier buy-in and support. This will require a significant technical discussion to be undertaken. In many ways this new solution can be proposed as a win-win. HIGHVOLT gets more stable delivery times and perhaps lower prices while the supplier gets larger order lots and the ability to schedule their production based on forecasts provided by HIGHVOLT. The risk also exists to the supplier that HIGHVOLT could move their business with this new solution to a different supplier entirely.

Another implementation challenge will be getting the sales engineers at HIGHVOLT to use these specific modules in their negotiations with customers. They must sell the new system. Similarly, the design engineers must be encouraged to use the new modularized portfolio in designing the unique systems for customers.

The business strategy decision to consider insourcing high risk components like the high-voltage capacitor cannot be ignored. In time, an argument can be made that developing the capability in-house to design and manufacture these high-voltage capacitors may be beneficial. When looking to assess the viability of in-sourcing, Fine recommends to assess whether the product is integral or modular. Then if one is capacity dependent and / or knowledge dependent upon the supplier [19]. At HIGHVOLT the current high-voltage capacitors are integral and HIGHVOLT is dependent on supplier only for capacity. This as-is state is reasonable to continue to outsource per Fine, though not ideal. The new proposed technical solution makes the high-voltage capacitors modular while HIGHVOLT continues to be dependent for capacity reasons only. The recommended transition to modular capacitor systems solidifies the current decision to outsource. In the move to source capacitance instead of capacitors, power shifts back towards HIGHVOLT from the supplier. While we can assert this case study is in line with an outsource decision, some tripwires to beware of are: rapidly changing technology in the field, continued unpredictable delivery schedules after the transition to the modular system and uncontrollable costs. If experiencing these tripwires, re-evaluation of the vertical integration decision should be undertaken.

A final business consideration is the possibility of sourcing the GFRP tubes from another Reinhausen Group company which currently produces them. Internal experts suggest that sourcing the GFRP tubes from a fellow portfolio company and then
supplying them to the capacitor supplier may further manage the timing risk and complexity associated with this problem. The strengths of this method stem from having visibility to the supply chain of the portfolio company while the current external supplier is known for prolonged, unexplained delays. Additionally, the concept of increased organizational proximity, which would be found in this arrangement, is noted as a means for improving the management of the supply chain [19]. This option will be explored in conjunction with technical discussions with the supplier.
6  RECOMMENDATIONS, CONCLUSIONS, FUTURE WORK AND PROGRESS TO DATE

6.1  Recommendations

6.1.1  Recommendations from Holistic Complexity Management Analysis

Summary

HIGHVOLT, while highly successful, can benefit from improvement in several areas. Noting the leadership's desire to manage complexity in order to increase revenue and decrease delivery time the following recommendations are made:

1. Address 10 immediate action issues as soon as possible
2. Plan for and undertake projects to address the 3 most correlated and impactful 'High Impact Areas'
   a. Investigate and plan a trial for specific project management on novel projects
   b. Source legal support for revision of existing and generation of new robust legal frameworks
   c. Appoint a project team to undertake an active timeline management initiative including SAP considerations
3. Undertake the 2 'Enabling Impact Area' projects
   a. Construct a standard specification clarification process and tools for ease of use
   b. Define responsibility for each activity down to the individual level

Immediate Action Items

Several issues came up repeatedly in interviews with company subject matter experts that seem necessary to solve quickly and can be classified as 'quick wins'. We have termed these issues 'immediate action issues'. They are listed below.

1. Ensure correct project classification at project initiation
2. Act upon kaizen ideas at control cabinet workshop
3. Expand the time scope in timeline planning meetings to meet the needs of the Operations Department
4. Correct replenishment timelines
5. Update test instructions based on running projects
6. Utilize Insulation Displacement Connectors (IDC) instead of screw type connectors
7. Evaluate cable tree use vs. point-to-point wiring
8. Create and use a cable length management tool
9. Generate and disseminate assembly directions for all projects before execution
10. Create standard language frameworks for the most common languages to expedite translations for work documents for installation and product documentations

**High Impact Areas with Highest Crossover Gain**

In evaluating the pain point classifications and correlations three were found to be the largest impact areas. If these high impact areas are properly addressed 59% of all the pain points expressed by company experts will be alleviated. (Undertaking the 'enabler impact areas' also brings the alleviated pain points to over 71%.) Not only do these projects represent the largest impact to reducing pain points, the associated pain points are also the most promising for large effects on delivery time and revenue generation. Of the twelve teams surveyed, six or more expressed pain points in each of these areas, demonstrating the pervasiveness of the issue across the company.

**Project Management**

For projects that are original (versus a repeated order), the overall project manager must be empowered, clearly visible and have defined responsibilities. This individual will care for the holistic health of the project including customer needs, operations support, progress and timeline management, specifications and modifications. They do not need to be the technical expert or the sales associate which secured the contract. A personality type demonstrating high network abilities and confidence to engage others throughout the complete organization is necessary. The people chosen must be empowered to dictate necessary steps to maintain the overall wellbeing of
the project. At a second level a multi-project coordinator is needed to co-ordinate the projects to allow a seamless execution in operations.

Justification examples from pain point data:

- “Communications channels are not standardized after an offer is placed, leading to various points of contact with the customer. This causes miscommunication, specification growth, and delays, thus increasing costs.”
- “Lessons learned are not captured on each project.”

Recommendation:
Establish a single point of entry for the customer with the issuing of the offer. Consequently, reject attempts by customers to bypass the single point of entry. This should help to improve the project clarification process between issuing the offer and getting an order. In addition, institute trial case studies with a devoted project manager. Consideration should be given to selecting top performing sales administrators for this position as they appear already skilled in complementary practices and, to some degree, already act in a project manager role.

**Legal Framework**

HIGHVOLT has the opportunity to better position itself to preserve company interests and revenue stream through improving utilized legal frameworks. More clear contractual agreements will help control specification growth, customer changes (without compensation), and warranty obligations.

Justification example from pain point data:

- “Vaguely constructed specification agreements leave significant room for interpretation. This causes discontent of the customer when what they imagined is not as HIGHVOLT planned, increasing costs stemming from changes, and inability to receive compensation for all capabilities provided to the customer. Perhaps a ‘not to do’ list would increase clarity within the legal framework.”
- “Suppliers are not held to contractual obligations for delivery time and quality, especially in single-source supply situations.”

Recommendation: undergo significant contractual review and revision with a skilled legal team. Additional legal consideration should be given to future business
opportunities like service contracts, data storage and processing opportunities, and/or leasing of test systems.

Timeline Management

Disparity between published timelines and feasible timelines creates frustration and delay while not providing for contingency planning. Some critical task areas are afforded significant timeline flexibility while others, though in more need of buffer, are not afforded any. Timelines are not updated at optimal intervals to keep all stakeholders apprised of progress or delays.

Justification example from pain point data:

- “The planning meeting scope is too short-sighted. This meeting should include a 6-week scope at a minimum, 7 is preferable.”
- “There is no dynamic updating to the milestone plan. It is done once and not modified.”

Recommendation: utilize SAP transition to institute more accurate timelines including a micro-scheduling tool capable of dynamic milestone tracking. Evaluate areas to build in time buffers and areas to constrain to rigid timelines. Extend planning meeting scope to a minimum of 6 weeks.

Enabling Impact Areas

Two pain point classifications are shown to be strongly supportive of the three highest impact areas: specification clarification and defining responsibility. Undertaking these projects in conjunction with the three projects discussed above offers the most relief to pain points and suggests the greatest ability to manage complexity to meet performance goals.

Specification Clarification

Disparity between specification wishes of the customer and agreements of HIGHVOLT creates significant cost increases and delivery delays.

Justification example from pain point data:

- “There is frequent use of non-approved text blocks in offers.”
- “In-house technical changes post factory acceptance testing occur.”
Recommendation: require specification clarification at earlier stages (legal framework impact area project assists) and utilize SAP transition to manage more clearly defined specifications. Single point of communication with the customer will also clarify this (project management impact area project assists).

**Defining Responsibilities**

Critical tasks do not have a single responsible party. Assigning a team responsibility for a task does not instill a sense of ownership and results in unnecessary delays.

Justification example from pain point data:

- “Sales administrators regularly take on tasks which they are not responsible for to 'make it happen'. This is not their work, but no one technically 'owns' it.”
- “Operators do not have decision rights to make minor or frequent changes without the input from the technical department. Then, after a delay, the technical department expresses frustration for having to solve the same problem again.”

Recommendation: clearly define responsible parties for all activities in documentation.

**6.1.2 Recommendations from High-Voltage Capacitor Case Study**

Negotiations with the supplier of the high-voltage capacitors is the next step to progress the portfolio modularization strategy and manage the complexity linked to this single-source supply issue. Technical discussions are required to know feasibility as well as determine souring strategies (forecasting models, etc.). The researcher recommends pursing these discussions as soon as possible as well as investigating other supplier potentials.

Additionally, another recommendation stems from the process of developing this new technical solution. In hindsight, the researcher took months to come up with the new proposed solution (path 1) while coming up with an improved solution (path 2) took a company expert about two days once he was asked to provide validation of path 1. Admittedly, he leveraged the researcher's previous work on path 1 to develop path 2. This, however, demonstrates how the company's siloed nature and self-organization of work has weakened innovation.
The cultural implications are again visible. Had the design engineer been encouraged to innovate and propose new solutions this single-source supply issue could have been resolved much earlier. The “defining responsibilities” impact area from the complexity management approach hopes to alleviate this empowerment issue further. This aspect of, ‘decisions aren’t made on the design engineer level’ prevented the ablest person from taking on the challenge—leadership actions should be taken to prevent this type of delay in the future. Enabling employees to be able to affect change in the broader process will surely yield more beneficial improvement ideas in the future. Additionally, building methods for transforming new knowledge developed through daily work tasks (tacit knowledge exercises) into useful work for others to build upon is necessary. Use of knowledge creation and capture frameworks, like that proposed by Nonaka, should be explored [7].

6.2 Conclusions

6.2.1 Summary of Work

This work treated a low volume high mix, highly technological, project company holistically for complexity management. Techniques are employed to identify, locate, analyze and then manage complexity. A case study validates the methodology developed.

As a summary, this research accomplishes the following:

- provide a framework with which to comprehend holistic complexity in a company
- demonstrate a methodology for discovery of complexity drivers
- suggest classification strategies to make the complexity data useful for action
- propose a method for ranking complexity drivers
- suggest actionable projects to help alleviate complexity where excessive (by reduction or reallocation)
- provide a case study on a risk and complexity driver with results validating the methodology of discovery
- demonstrate a useful case of product portfolio modularization to influence supply chain dynamics
suggest a novel reason for modularizing a product portfolio—to alleviate a single-source supply issue

6.2.2 Limitations of the Methodology

This method of data collection is well suited for companies similar in size to HIGHVOLT (approximately 240 employees). Beyond this size it is questionable if the same one-on-one data collection from critical teams would be able to provide the same insight into the complexity resident in the process, products and organization. Perhaps applied to individual departments at larger companies would be a way to retain fidelity of the process and quality of the results. Additionally, due to scope and time constraints related to this project further quantification methods were not explored. The following Section 6.2.4 suggests follow-on methods to improve the quantification of the methodology.

6.2.3 Generalizing the Findings

The theoretical framework posed by the researcher is general in its nature with intent. Every firm experiences all four types of complexity: process, product, organizational and market driven. We wish to make a tool with broad applicability to meet needs of companies for which the current work done on product complexity regarding high volume-low mix manufacturing does not fit and rapid results are needed for executive level decision making. In environments where the workforce responds well to digital survey, it may be possible to employ this type of complexity management with significantly less man-hours required on the part of the researcher. In smaller organizations this type of method can be employed more often as part of a continuous improvement project. This method serves as a ‘quick response’ model with the ability to build upon the framework with application of techniques like those suggested in the following, future work, section.

6.3 Future Work

In future application of this framework, employing quantitative analytic methods to assist in the ranking of the impact areas, planning coordination and quantifying benefits of projects will be helpful. Employing design system matrix (DSM) techniques as well as multi domain matrix (MDM) methods to assist in complexity quantification is possible from process, product, portfolio and organizational perspectives. Using
these techniques in conjunction with novel complexity quantification measures, like integrative complexity as recently described by Sihna, Suh and de Weck, can provide useful numerical data to aid in the prioritization of projects, understanding interrelatedness and highlighting problem areas [9]. Future data collection rounds in association with this type of project at HIGHVOLT should prioritize formatting of data in line with DSM and MDM methods to enable use of these new complexity metrics.

Where possible, using time based activity based costing models may also provide more clarity to the ranking process. Building upon this work to quantitatively measure the impact of the complexity management technique would be beneficial and would require correlating time effort to dollars and capacity saved or changed for each aspect of complexity management technique employed. Utilizing Gantt chart comparisons for ‘before’ and ‘after’ process flows can aid in this quantification effort. At the time of this research, ‘after’ Gantt charts are not available nor are idealized ones refined enough for analysis. This methodology would benefit by their use over longer scale research projects.

Exploring in which areas modularization strategies may be useful, but are currently not being employed is of significance. Demonstrating that modularization can alleviate complexity and risk drivers in this project (even if not reducing cost/part) brings question as to where else modularization strategies may be useful. The spectrum of application of modularization strategies appears broader than foundationaly assumed.

6.4 Progress as of Date of Publishing

As of the date of this thesis many of the recommendations suggested by this project have been undertaken at HIGHVOLT. This summary is provided as further evidence of the usefulness of the methodology developed.

Technical discussions and negotiations with the high-voltage capacitor supplier regarding the new technical solution developed in this research have yielded impressive results. The supplier has enthusiastically agreed to pursue the modularization strategy and anticipates delivery times to reduce from the current 14 to 18-week window to only 2 weeks. Significant cost savings for HIGHVOLT are also expected.
Additionally, many of the immediate action items have been solved or are in progress.

1. Achieved Q1 of 2018: Ensure correct project classification at project initiation
2. Work in progress, to be finalized Q2 of 2018: Act upon kaizen ideas at control cabinet workshop
3. Work in progress, to be solved in Q2 of 2018: Expand the time scope in timeline planning meetings to meet the needs of the Operations Department
4. Issue passed to team responsible for SAP migration project: Correct replenishment timelines
5. Partially introduced at time of publishing, full rollout of solution (spring clamps instead of IDCs) will be complete by end of 2018: Utilize Insulation Displacement Connectors (IDC) instead of screw type connectors
6. Planed for 2019: Evaluate cable tree use vs. point-to-point wiring
7. Included in work done by SAP migration project team: Create and use a cable length management tool
8. To be finalized by end of 2018: Generate and disseminate assembly directions for all projects before execution
WORKS CITED


APPENDIX A: RESONANT, HIGH CURRENT AND MODULE SYSTEMS [5]

**RESONANT TEST SYSTEMS WITH FREQUENCY CONVERTER**

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
</tr>
</thead>
</table>
| WRV G and WRVG G | - Oil or SF₆ insulated HV reactors  
- For GIS testing  
- Directly flanged to test object  
- Factory and on-site use |
| WRVT | - Steel tank HV reactors  
- For testing HV cables on site or for submarine cables in factory  
- Use of multiple systems for long cables |
| WRVTM | - Steel tank HV reactor  
- For testing MV cables, motors and generators  
- Compact size, low weight |

**HIGH CURRENT TEST SYSTEM**

- **WRVM**  
  - Insulating case HV reactors  
  - For testing GIS and transformers (applied voltage)  
  - Compact size, low weight  
  - Factory and on-site use

**HV MODULE TEST SYSTEMS**

- **HCTS**  
  - Fixed or hinged core transformers  
  - For testing MV/HV cables, connectors, switchgears, etc.  
  - Integrated compensation  
  - Highly flexible modular test system setup  
  - For student education

**TECHNICAL PARAMETERS**

<table>
<thead>
<tr>
<th>AC test systems 50/60 Hz</th>
<th>Voltage ratings</th>
<th>Current ratings</th>
<th>Test power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test system</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transformer insulating case (AP PCC)</td>
<td>100...1000 kV</td>
<td>up to 1 A</td>
<td>up to 1000 kVA</td>
</tr>
<tr>
<td>Transformer steel tank (AP FEK)</td>
<td>80...1000 kV</td>
<td>up to 10 A</td>
<td>up to 3000 kVA</td>
</tr>
<tr>
<td>Transformer SF₆ insulated (AP G)</td>
<td>51...1500 kV</td>
<td>up to 0.78 A</td>
<td>up to 900 kVA</td>
</tr>
<tr>
<td>Resonant reactor, modular (WRG)</td>
<td>250...1500 kV</td>
<td>up to 112 A</td>
<td>up to 6800 kVA</td>
</tr>
<tr>
<td>Resonant reactor, two taps (WR)</td>
<td>6...200 kV</td>
<td>up to 820 A</td>
<td>up to 6800 kVA</td>
</tr>
<tr>
<td>Resonant reactor, high charge (WRU)</td>
<td>45...350 kV</td>
<td>up to 50 A</td>
<td>up to 10000 kVA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>AC resonant test systems with variable frequency</th>
<th>Voltage ratings</th>
<th>Current ratings</th>
<th>Test power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test system</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>For GIS testing (WRVG G)</td>
<td>400...750 kV</td>
<td>up to 1.5 A</td>
<td>up to 2 MVA</td>
</tr>
<tr>
<td>For transformer, GIS and short cable testing (WRV M)</td>
<td>440...800 kV</td>
<td>up to 10 A</td>
<td>up to 5 MVA</td>
</tr>
<tr>
<td>For HV cable testing (WRV TM)</td>
<td>110...320 kV</td>
<td>up to 50 A</td>
<td>up to 5 MVA</td>
</tr>
<tr>
<td>For MV cable testing (WRV TM)</td>
<td>35...50 kV</td>
<td>up to 25 A</td>
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<th>AC high current test systems for heat cycle testing</th>
<th>Voltage ratings</th>
<th>Current ratings</th>
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<td>Test system</td>
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<td>High current test system (H-CTS)</td>
<td>up to 7000 A</td>
<td>up to 100 V</td>
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APPENDIX B: DC AND IMPULSE TEST SYSTEMS [5]

DC AND IMPULSE TEST SYSTEMS

DC VOLTAGE TEST SYSTEMS

GP
- High power DC test system
- Extremely high voltage available
- Continuous operation

FGP
- High power DC test system
- Outdoor system for testing of outdoor HV equipment
- Continuous operation

GPM
- Compact, powerful DC modules
- Mobile and stationary use
- Integrated HV divider

IMPULSE CURRENT AND VOLTAGE TEST SYSTEMS

IPS
- For testing arresters, fuses, etc.
- Low inductance design for optimum wave shape

IPL
- Low inductance design for optimum wave shape
- Modular design for on-site testing
- Resistor storage at each stage for series G

IPM
- High power DC test system
- Outdoor system for testing of outdoor HV equipment
- Continuous operation

IPG
- Compact, powerful DC modules
- Mobile and stationary use
- Integrated HV divider

<table>
<thead>
<tr>
<th>AC induced voltage test system for transformers and rectifier testing</th>
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<td>Power transformer test system (HV+HCOS)</td>
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<td>DC test systems</td>
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<td>DC system (conventional, GP)</td>
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<td>Outdoor DC system (FGP)</td>
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<td>DC module system (GPM)</td>
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<td>Impulse current test systems</td>
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<tr>
<td>Impulse current test system (IPS)</td>
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</table>

Test system Build-up tests

- Small impulse test system (IPL) | 100…1200 kV | 100 kV | up to 65 kJ |
- Medium impulse test system (IP M) | 500…2400 kV | 100 kV | up to 200 kJ |
- Large impulse test system (IP G) | 1000…5000 kV | 2 x 100 kV | up to 960 kJ |
APPENDIX C: CONTROL AND MEASURING EQUIPMENT AND ACCESSORIES [5]

CONTROL AND MEASURING SYSTEMS, ACCESSORIES

MEASURING SYSTEMS

- HIRES transient recorder
  - Flexible hard- and software configuration
  - Manual and automatic measurements
  - Potential free probes available
  - Extremely EMI proof for exact results in harsh conditions

- LMOS transformer loss measuring system
  - Load and no-load loss measurements
  - One compact unit containing voltage and current sensors
  - Disturbance free optical data transmission

- PIDAS partial discharge measuring system
  - For power and distribution transformers, cables, GIS and other components
  - Disturbance free optical data transmission
  - Factory and on-site tests

ACCESSORIES

- Connection Point
  - For impulse test systems
  - Voltage divider, chopping gap and overshoot compensation in one device
  - Time and space saving

- Dividers and shunts
  - Available for current, voltage, tan delta, PD, capacitance, etc.
  - Calibration traceable to national PTB standards
  - Available as reference measuring dividers

- HIRES Locator
  - Breakdown location on-line or during HV testing
  - Cable lengths > 200 km
  - Applicable for all AC and DC cables

- Control system HCOS
  - Unified control system for all HV test systems
  - Integrated safety system
  - Measurements of all tests in one protocol
  - Integrated data base

- Cable end termination system
  - Used as PD free cable end termination during HV tests
  - Automatic water conditioning unit

- Shielded room
  - Low background noise level for sensitive PD measurement during HV tests
  - Various sizes available
  - Including ventilation, air conditioning, control rooms, air cushion floor, etc.
APPENDIX D: PAIN POINT DATA COLLECTION SHEET

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87
APPENDIX E: ACTIVITY DESCRIPTION SHEET
APPENDIX F: PARTITIONED TOP-LEVEL DSM FOR IMPACT AREA CLASSIFICATION RELATIONSHIPS

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