OPTIMAL PERSONNEL DEPLOYMENT STRATEGY FOR SELF-PERFORM MAINTENANCE ON WIND FARMS

A Thesis

by

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ABSTRACT

Wind turbine maintenance is a major cost factor and key determinant of wind farm productivity. Many companies outsource critical maintenance procedures while others perform these tasks in-house, referred to as self-perform maintenance. While expected to reduce time to profit on asset investment, self-perform requires an efficient personnel deployment strategy to implement. In this thesis, a partial solution to the optimization of wind turbine maintenance personnel team assignment is presented.

A holistic framework is established, through analysis of historical work orders, for defining metrics that evaluate the performance of technicians. These metrics are further transformed into interpretable proficiency coefficients to be incorporated into an application of the team assignment problem.

A case study of a large wind farm owner and operator is presented to illustrate the potential benefits and caveats of the proposed metrics and evaluation strategy. Additionally, the practicality of the data-derived metrics and proficiencies is illustrated. Key improvement strategies in data quality and metric aggregation are detailed, as well as discussion of a potential formulation of the task-to-team assignment problem, to be modeled through a standard maximin approach and solved through an integer programming technique.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1 Problem Statement

Electricity sourced from renewable forms of energy production, such as wind and solar energy, accounts for an ever-increasing proportion of consumer needs, both at a small and large scale. Technologies that harvest energy from responsible sources have become more widespread in the past decade as governments have clearly supported their development. In 2016 alone, renewable energy accounted for 59% ($10.9 billion) of the total energy-related tax preferences and has outpaced fossil fuel tax preferences since 2008[40]. Yet, even with such a sustained focus on subsidizing renewable forms of energy, growth must be supported with accompanying advancement in technology.

Current renewable energy technologies are subject to the intermittent nature of the energy source itself. For example, wind turbines only capture energy when the wind source is consistently strong enough to rotate the blades. Therefore, focus must be placed on the efficient use of the technology so that, when conditions present themselves, the maximum amount of energy can be extracted.

Over the previous decades of fervent deployment of wind turbines, there has been a significant shift in the perceived contribution of operations and maintenance to the value of an enterprise. Historically, it was believed that a majority of the value was attributed to the initial manufacturing and development of the wind turbines and that post-development value generation was relatively constant. Yet, as wind farms and technologies became more mature, the role of operations and maintenance has been shown to have an enormous effect on the regularity of an asset's profit generation. In the Winter 2008 volume of McKinsey & Company's Electric Power and Natural Gas, they laid out the importance of comprehensive operations and maintenance practices.

> "Our research… suggests that operations and maintenance (O&M) can play an important role in maximizing the returns of existing assets and increasing revenues from existing wind farms. Depending on existing levels of performance, improved O&M could account for nearly a 20 percent increase in the equity internal rate of return … Companies that identify and systematically capture this potential could then develop a key competitive advantage in the industry"[86]

Operations and maintenance for a wind farm can be sub-divided into three main levers: availability, efficiency, and operations and maintenance costs. It must be noted that these three levers are not independent of one another. It can easily be shown that unavoidable events, such as inclement weather, can cause lapses in wind farm performance, thereby causing an increase in operations and maintenance costs to maintain specific levels of availability and efficiency. By understanding this connection between availability, efficiency, and operations and maintenance costs, certain inferences can be made about critical factors which have great effect on wind farm operations and maintenance practices. Most obvious of these critical factors is the effectiveness with which maintenance practices tackle and solve issues affecting availability, efficiency, and operations and maintenance costs.

To focus research on increasing the effectiveness of a wind farm’s maintenance practices, it becomes convenient to generalize to several major operations and maintenance policies. Such generalizations typically fall into three major categories: full-service, self-perform, and hybrid. According to Martin, et al. 2008, a full-service maintenance policy is commonly contracted directly to the wind turbine original equipment manufacturer with some guaranteed level of performance. A self-perform maintenance policy is exactly the opposite, where the wind farm internally performs all maintenance activities on wind turbines with their own teams. A hybrid maintenance policy is a combination of full-service and self-perform models such that the wind farm owner and operator performs certain maintenance activities while contracting out others.[86]

While the hybrid policies are currently the most commonly observed, certain wind farms are actively seeking to transition to the self-perform model. The self-perform maintenance policy enables a cost neutral point on an asset investment earlier in its life, thus shortening overall time to profit. Yet, self-perform maintenance transformations are incredibly complex and require highly coordinated implementation. This is chiefly due to two main issues which are often overlooked.

Firstly, transitioning from a full-service (or hybrid) model to a self-perform model requires wholly transferring the skills and knowledge of the wind turbine original equipment manufacturer maintenance staff to the staff of the wind farm owner and operator. The nuances of this transfer are particularly complex. Many wind farms have a variety of different wind turbine models which technicians must be proficient in servicing. Additionally, these various models of wind turbines are often subject to many different environmental conditions and factors, i.e. geography, climate, weather. Further compounding this complexity is the fact that there are a large multitude of different services and faults which must be performed. Thus, the amount of required historical and technical knowledge is vast. The most basic method of attaining this knowledge and experience is through a period of transition where wind farm technicians shadow and learn from original equipment manufacturer technicians. Even after this transitional period, however, continual communication is often required if new, unique, or difficult issues present themselves.

While the transfer of knowledge is indeed a challenging issue to deal with, the fact that the pool of maintenance technicians at major wind farms contains a certain number of tenured technicians does help. These tenured technicians have backgrounds servicing a wide variety of different turbine models across different sites and for different types of service (in fact, tenured technicians are often former original equipment manufacturer technicians). By supplementing the presence of experienced technicians and their knowledge with formal training, the basic transfer of required maintenance knowledge can be fulfilled.

Secondly, and of primary interest to this research, all assets must be managed and deployed in an efficient manner to realize true benefit. In this sense, benefit can be described as achieving the most efficient and highest quality (1) resolution of technical services and issues and (2) internal transfer of skills and experience among technicians.

The topic of efficiently managing and deploying wind turbine maintenance assets has been explored vigorously in previous research. As will be discussed in Section 2.3, previous focuses have centered around deployment of resources based upon failure-based, time-based, and condition-based models, amongst others. However, as will be discussed, there is a significant gap in the understanding of the effect of maintenance team composition. To support a major wind farm owner and operator in their transformation from a full-service or a hybrid to a self-perform maintenance policy, this gap will be explored and solutions will be proposed in this thesis.

1.2 Research Objectives

A pre-requisite of successful maintenance is a successful team of maintenance personnel. While most research in wind farm maintenance efficiency and deployment defines an effective and skilled team in terms of a successful operation, this proxy is insufficient. In truth, by treating maintenance teams as constants, a vast area of unexplored potential is being neglected. The aim of this research is to explore this area by treating the team of maintenance personnel as a dynamic composition from a pool of skilled workers.

To accomplish this goal, a holistic framework is developed to enable the generation of technician performance metrics using historical work orders. An expert survey is carried out to define applicable performance metrics. Additionally, systematized work order grouping and work order filtering and data cleaning strategies are proposed. Metrics are calculated for each work order and then aggregated to the respective assigned technicians. After aggregation and normalization of data, the performance metrics are organized into an easily interpretable format, dubbed the Technician Proficiency Matrix.

Execution of these processes is illustrated in a case study of a large wind farm owner and operator from January 1, 2017 to March 15, 2018. Technician Proficiency Matrices are calculated for each technician and three (3) distinct use cases are illustrated. Through the evaluation of these use cases, the practicality of using a data-driven method of technician performance metrics and proficiencies is demonstrated.

1.3 Organization of Thesis

Following this introduction, a detailed literature review is presented in Chapter 2 showing supporting evidence that the proposed research is indeed novel. In Chapter 3, a research methodology is established to provide a systematic framework for the reader to contextualize the performance metric development and calculation. A case study of a major wind farm owner and operator is conducted in Chapter 4 for illustration of performance metric applicability. A discussion is presented in Chapter 5 which illustrates key data quality and performance metric weighting strategies. Additional discussion is presented for technician assignment modeling proposals, supported by material in the corresponding appendices. Finally, conclusions to the Personnel Deployment Strategy are presented in Chapter 6.

2. LITERATURE REVIEW

The following literature review was completed per three main stages: 1) input, 2) processing, and 3) output. Input is identified as the stage where all relevant literature is collected to form the Relevant Body of Knowledge. Processing is the stage where the collected literature is reviewed, parsed, and sorted based on themes relevant to the proposed research and their potential contribution. Output is the stage where the resulting themes and subsequent gaps are evaluated.[82]

Inherent in the literature review process is the rise and fall of the quantity of publications of the Relevant Body of Knowledge. However, as the review progresses from the first to the last stage, the relevance of the publications to the proposed research objectives dramatically increases. An effective literature review will have comprehensively defined the Relevant Body of Knowledge such that a proposed research path addresses an absent or ill-defined area of knowledge or application, if such an area exists.

For a detailed breakdown of individual literature review steps, see Appendix A.1 for Input, A.2 for Processing, and A.3 for Output.

2.1 Relevant Body of Knowledge

The Relevant Body of Knowledge is visually represented in Figure 1. The visual depiction is useful in exhibiting inherent thematic divisions and allows one to quickly identify absent or ill-defined areas of research. Notes meant as a primer in analyzing the visual depiction of the Relevant Body of Knowledge are detailed in Appendix A.4.

The numbers after commas in the outer ring of each thematic division in Figure 1 indicate the number of publications categorized into that thematic division. An important clarification is that the sum of publications over all thematic divisions does not equal 136 (the total number of publications in the literature review). This discrepancy is due to certain publications containing information lending itself to multiple categorizations. Therefore, these publications are counted in multiple thematic divisions. The total sum of publications referenced over all thematic divisions is 153 but, by removing duplicate instances due to multiple categorizations, the total number of unique publications is 136.

It can be seen in Figure 1 that there is relative saturation in performance measurement and management, maintenance modeling and management, and reliability analysis when considering the maintenance function in the wind industry. Yet, only one relevant publication, Bos and Chatterjee 2016[22], has been found in team optimization with respect to the maintenance function in the wind industry. This indicates that the proposed research, development of performance metrics for use in optimization of maintenance team composition in the wind industry, is indeed novel. As the proposed research path incorporates elements from all thematic groupings, what follows is a brief analysis of each major area.

Additionally, a distribution of the different types of publications incorporated into the Relevant Body of Knowledge is provided in Figure 2, with a full breakdown listed in

Appendix A.6. The full listing of all publications respective to their thematic grouping has been provided in Appendix A.5.

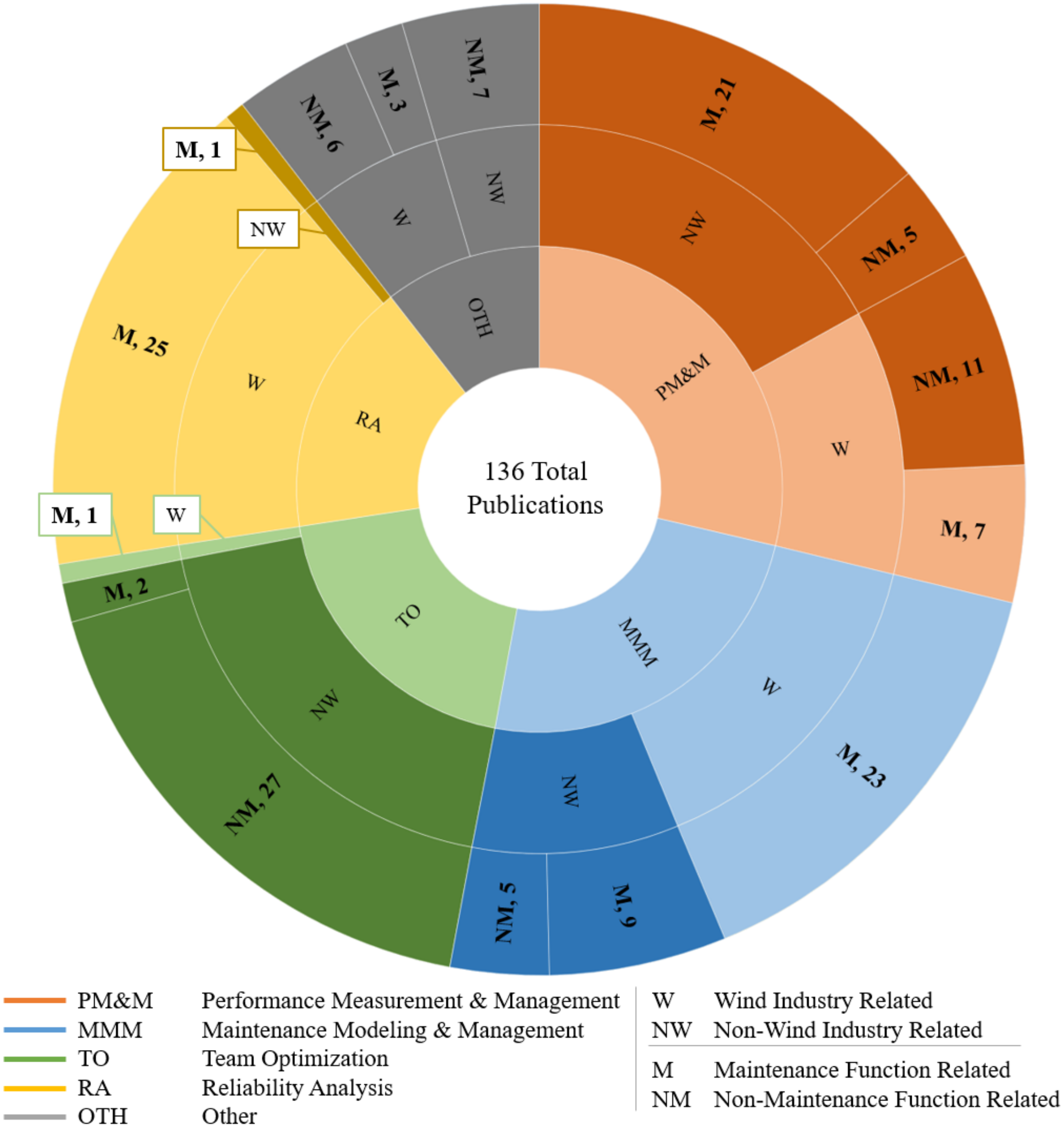


Figure 1: Relevant Body of Knowledge

(Numbers indicate number of publications categorized into specific thematic division)

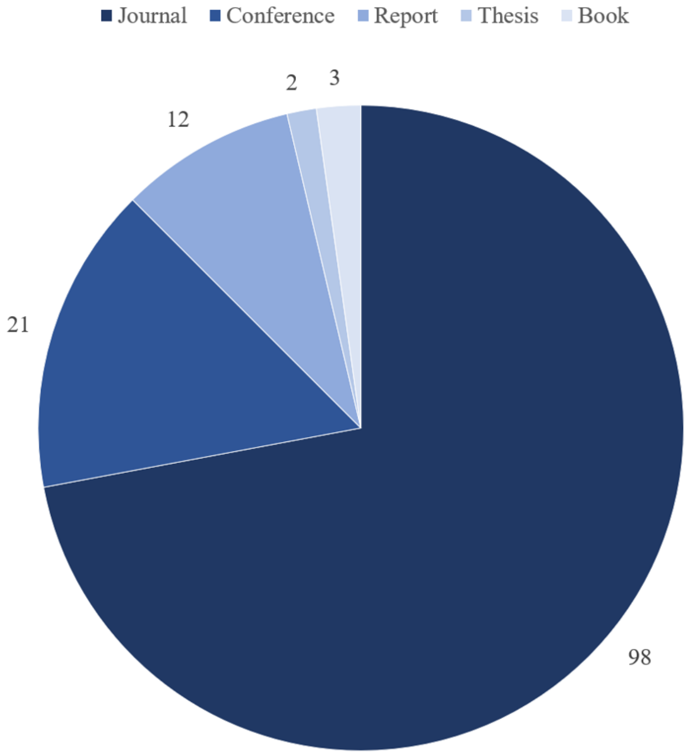


Figure 2: Summary of Literature Review Sources
(Numbers indicate number of publications of that type in literature review)

2.2 Performance Measurement and Management

As with the understanding of the criticality of operations and maintenance, the perception of performance measurement and management (PM&M) has radically changed over the last two decades. A proclamation from the Harvard Business Review called for a shift "from treating financial figures as the foundation for performance measurement to treating them as one among a broader set of measures".[45] Since this manifesto, many different essential departments have developed and committed metrics to aid in holistic PM&M, prominently among them, the maintenance function within operations and maintenance. "For many asset-intensive industries, the maintenance costs are a significant portion of the operational cost".[96] Even now, after decades of invested research, the role of the maintenance function in PM&M is still evolving with the emergence of the importance of big data and data management in decision making. "The ongoing industrial digitalization provides enormous capabilities for industry to collect vast amount[s] of data and information (i.e. industrial big data), from various processes and data sources such as operation, maintenance, and business processes."[69] To evaluate the holistic research of PM&M in the maintenance function, the continual development of performance indicators and performance management frameworks must be examined.

A performance indicator is a metric which can compare actual performance with specific referenced or benchmarked performance. Consequently, when performance indicators are aggregated across various levels of an organization to present performance at a managerial level, it is designated a key performance indicator.[95] However, proper performance management frameworks are needed when presenting key performance indicators to management. Per Parida, et al. 2015, performance management frameworks are typically categorized as one of the following: traditional accounting based, multi-criteria frameworks, multi-criteria hierarchical, function specific, and business specific.[96] The benefit of having a rigorously vetted performance management framework is its ease of implementation in practical applications.

Of utmost importance to the proposed research is to develop a methodology of translating maintenance team composition optimization results through key performance indicators to wind farm management. Initial review into performance management frameworks in the wind industry revealed a few examples of active research, chiefly among them, a study of a balanced scorecard implementation at a wind farm by Schneider and Vieira 2010. Schneider and Vieira set out to "develop a suitable framework for establishing key performance indicators… to enable the company to compress and streamline management decision-making…".[105] While this research presented a relevant application, the developed key performance indicators were not specific enough to apply directly. Therefore, for the proposed research it was decided to constrain the performance management framework to the "function specific" category and create novel key performance indicators, i.e. performance metrics and proficiencies, to convey representative results.

2.3 Maintenance Modeling and Management and Reliability Analysis

Proper deployment of maintenance assets is critical to achieve minimal asset production costs and has been quite vigorously explored in the last two decades. This field of research, maintenance modeling and management (MMM), is distinctly structured in two major areas: 1) reliability analysis (RA) and 2) leveraging the reliability prediction.

RA is mainly concerned with the development of "physics-based and data-driven"[61] tools and models to aid in turbine performance evaluation. As stated by He and Kusiak 2018, "Assessing performance of a wind turbine is difficult due to inherent nonlinearity between the input (wind speed) and the output (power generated). It is further complicated by the distribution of faults across the working envelope."[61]

Physics-based models have historically centered around the use of fatigue analysis. These models, somewhat specific to different turbine types, locations, and timeframes, use component failure rates and probability distributions to inform maintenance decisions. While attractive because of their grounding in known systems and interactions, physics-based models tend to succumb to the sheer complexity of competing factors present in wind turbines.

Data-driven models are not as susceptible to the same restrictions that tend to plague physics-based models. “The data-driven approaches have been used to model different phenomena in wind turbines, including visualizing performance of wind turbines. Prediction of wind power is key to anticipating changes in performance of wind turbines.”[61] Historical methods of data-driven turbine performance evaluation range from simple time series modeling to more complex machine learning algorithms such as neural networks and support vector machines, amongst others. Ding, et al. 2013 and He and Kusiak 2018 completed significant reviews of prevalent methods and models used in RA.[42,61] Each details a sample of the many different approaches that can be used to deliver predictions of turbine performance and reliability.

Complementing RA, leveraging the reliability prediction is concerned with the proper use of information from RA tools and models in developing maintenance asset deployment strategies. By “leveraging the reliability prediction, a maintenance program can be developed and implemented such that the system availability is guaranteed during [the] 20 [year] lifetime”.[42]

In general, there are three broad categories of wind turbine maintenance: corrective, scheduled, and condition-based maintenance.[101] However, a more specific and applicable categorization is failure-based, time-based, and condition-based.[42] Failure-based maintenance is that which is completed based on faults and diagnostic reports confirming a failure has occurred. Time-based maintenance is that which is usually concerned with continual upkeep of the turbine and is performed at regularly scheduled intervals. Condition-based maintenance "is the most advanced maintenance scheme as the performance of components can be actively tracked based on the condition monitoring (CM) apparatus, hence an aging component can be pro-actively replaced prior to the occurrence of the failure."[42] While the vast amount of research in this field is continually evolving, most is in some way shaped from these three core maintenance practices.

An emerging field of study is the role of opportunistic maintenance and grouping maintenance activities. Opportunistic maintenance simply entails parallel maintenance activities and is usually the combination of failure-based or condition-based with time-based maintenance. "When a downtime opportunity is created by a faulty unit, maintenance team[s] [perform] preventative maintenance on other components that are still functional yet exceed a pre-degradation threshold. Consequently, substantial cost can be avoided as oppose[d] to separate maintenance actions."[42] Other important aspects of this field include the prevalence of research with respect to offshore wind turbines and the focus on optimizing maintenance assets against the stochastic nature of the environment, as noted by El-Thalji and Liyanage 2012.[49]

The main application of this line of research is in building the knowledge of maintenance modeling and deployment strategies for wind turbines. By incorporating this knowledge, procedures can be created and enacted more efficiently. This understanding will come in especially useful when considering the generation of performance metrics and in their application. This will require an understanding of likely-to-fail components and systems as well as of typical trade-off and risk balancing considerations.

2.4 Team Optimization

In general, team optimization (TO) is not a novel concept and is considered an application of combinatorial optimization, mainly referred to by a well-known subset of problems called the Assignment Problem. “Assignment problems deal with the question of how to assign *n* items (jobs, students) to *n* other items (machines, tasks).”[26] The assignment problem has an extensive research history in both theoretical development and practical applications. Specifically of interest to the proposed research is the integer program formulation, a sub-category of linear assignment problems.

Applications of TO in combinatorial optimization are vast and include team formation for engineering projects[66,67,140], sports[4], military operations[44], manufacturing[112], and aircraft maintenance[39], amongst many others. However, what is clear is that there is no definitive application of the assignment problem to maintenance personnel in the wind industry, especially with respect to using individual attributes or evaluating specific types of tasks. This oversight is partly due to the typical treatment of maintenance teams as constants in MMM. Most wind maintenance team applications treat all maintenance teams as interchangeable, with only slight thought to certification requirements.

While the proposed application of the assignment problem appears to be completely novel, a relevant publication was identified. Bos and Chatterjee 2016 establish a framework for hiring suitable wind service technicians. Considerable criteria, including knowledge, skill, ability, personality, physical attributes, and mental fitness, is obtained through various interviewing and testing methods.[22] This research is relevant to the proposed research save a few major differences.

Firstly, the authors focus on the hiring of wind service technicians rather than an already available pool from which to choose. This difference is significant in that technicians being considered for hiring are unlikely to have the significantly developed skills or certifications required to perform certain tasks that seasoned technicians will have. New technicians also do not usually have a historical record of work completed or available, rendering many performance metric calculations impossible.

Secondly, the authors use Fuzzy Set Theory to define their attribute weighting system. "Fuzzy Set Theory is used to handle immeasurable or numerically inexpressible information and to make all information uniform."[22] In the proposed research, a concerted effort is made to use data-driven methods to derive attributes while limiting subjectivity.

3. METHODOLOGY

To create a repeatable procedure for establishing a holistic framework for generation of the Technician Proficiency Matrix, the following actions were taken:

1. An expert survey was coordinated and completed
2. A work order grouping strategy was identified
3. A work order filtering and data cleaning strategy was defined
4. Results were used to generate performance sub-metric calculations for individual work orders and for technicians
5. Work order metrics were isolated to technicians and aggregated into a Technician Proficiency Matrix

Graphical representation of this process can be seen in Figure 3.

The following methodology was developed in close collaboration with the large wind farm owner and operator for which the case study was completed. One item to note is that many of the specific terms for work order types, functional locations, databases, and data fields in the following sections refer to specific terms used by the large wind farm owner and operator for which the case study was completed. The reader should be aware that, given a different application of the Personnel Deployment Strategy, many of these specific terms drawn from the current application will be different. The application specific nomenclature is summarized in Appendix B.1.

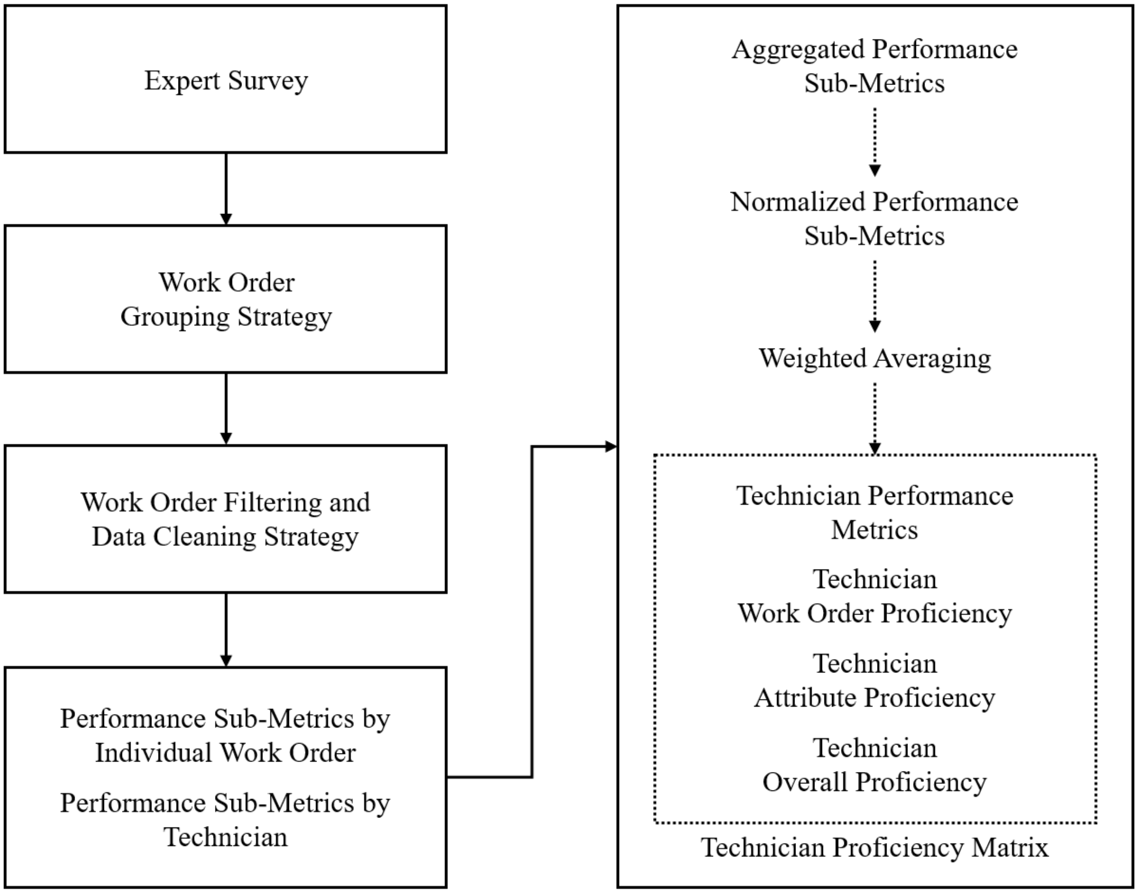


Figure 3: Holistic Technician Performance Metric Generation Process

3.1 Expert Survey & Results

The first step in developing metrics for any industry specific application should almost always be to conduct a survey of experts in the relevant field. By consulting experts in the application for which the metrics are to be developed, a measure of fairness is achieved. As stated by Tsang 1998, “The adoption of fair processes is the key to successful alignment of these goals. It helps to harness the energy and creativity of committed managers and employees to drive the desired organizational transformations.”[122] By involving technicians at different hierarchical levels in the organization in the development of their own performance metrics, successful stakeholder involvement is achieved. To create technician performance metrics for a large wind farm owner and operator, a survey of 13 technicians, senior technicians, operations managers, and directors was completed. A series of 12 questions were posed to survey participants, shown in full in Appendix B.2.

While all questions yielded contextual information important to grasp internal operations, protocols, and opinions on working conditions and policies, only the first question is considered when developing performance metric structures, repeated below, from Appendix B.2.

> What are the metrics by which you would rate a technician's performance, given they were assigned: 1) a single task, 2) multiple tasks of the same turbine type, location, and weather conditions, and 3) multiple tasks of differing severity, turbine type, location, and weather conditions?

This question relates directly to the goal of developing a consistent set of metrics by which to rate maintenance technicians in the wind farm application. It is important to note that many respondents offered multiple, independent statements in answering the first question, explaining the discrepancy between the number of responders and total "occurrence", seen below in Figure 4.

Some items to take note of in Figure 4 are with respect to safety, preparedness, completeness, productivity, consistency, and the human factor. Firstly, an overwhelming number of participants mentioned that safety was extremely important and that it should not be sacrificed in any way for the sake of a quicker task completion. Safety itself is measured through other means outside of the scope of this research, and thus, will not be included. Secondly, preparedness, completeness, productivity, and consistency are conceptually contained within the quality and efficiency metrics. Thirdly, multiple participants viewed the effect of the human factor as extremely important. While the human factor is prevalent and always present, it will not be considered in the scope of this research due to the complexity it introduces.

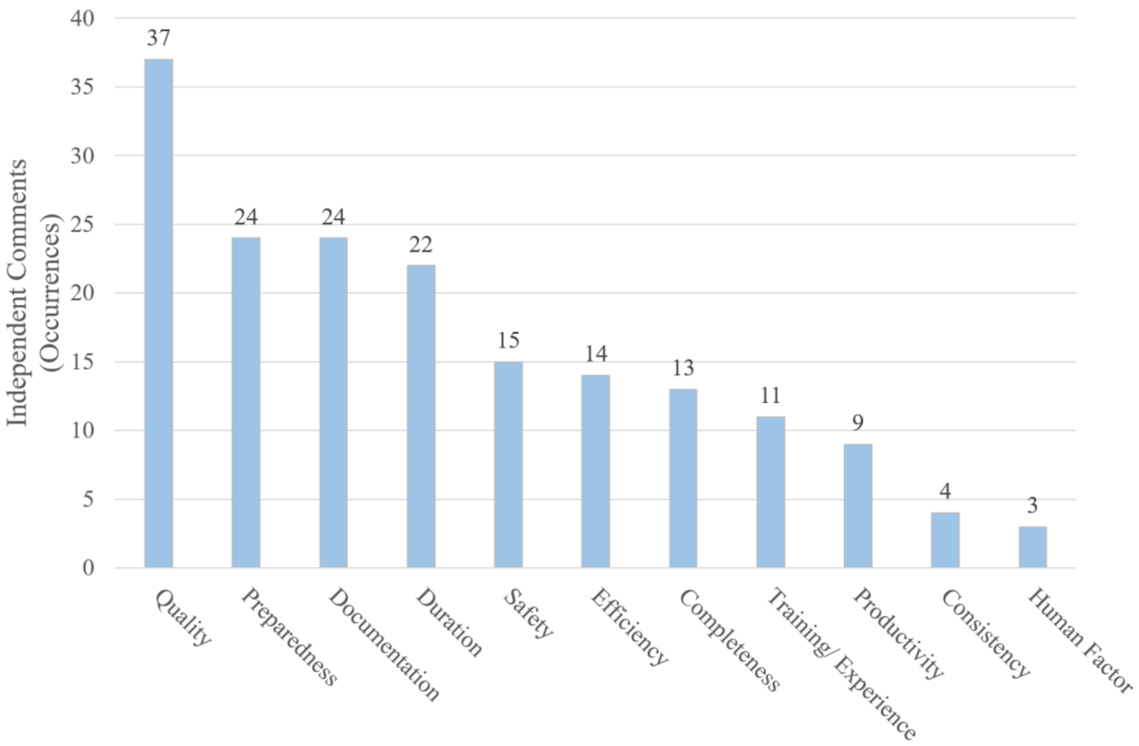


Figure 4: Expert Survey Performance Metric Results

The resulting metrics declaration of the expert survey is as follows:

Declaration: Safety is our highest priority and shall not be sacrificed at the expense of any other performance metric

Work Order Specific Performance Metrics

1. Quality (Q) – defined as the consistent "right-first-time" completion of tasks
2. Timeliness (T) – defined as the speed in "right-first-time" completion of tasks
3. Efficiency (E) – defined as the best use of time spent in "right-first-time" completion of tasks
4. Documentation (D) – defined as the consistent, correct, and complete submission of work order documentation

Technician Specific Performance Metrics

5. Task Completion Rate (TCR) – defined as the historical and recent "right-first-time" completion of specific order types
6. Task-Based Certification (TBC) – defined as the acquired knowledge and certification necessary to excel in Quality, Timeliness, Efficiency, and Documentation

3.2 Work Order Grouping Strategy

An important factor to consider when creating fair technician metrics is the complexity and similarity of tasks being compared. Certain similarly categorized tasks may have completely different levels of complexity involved in achieving a solution. For example, even though two faults may technically be considered the same order type (“reactive”), the fault complexity of addressing a “yaw limit switch activated” may be completely different than that of a “pitch thyristor 3 fault”. In an ideal case, calculating metrics of the completion of one task should not be compared to metrics on the completion of the other task if their complexities are vastly different. Therefore, a discussion on the grouping of work orders to compare similar complexity work is required.

In a theoretical sense, the best comparison method would be an exact like-for-like comparison of work orders. An example of this would be that metrics on the completion of a “gearbox oil overtemperature” fault in turbine Y at functional location “… – GBX”, where “GBX” designates “gearbox”, would only be compared to those metrics of other “gearbox oil overtemperature” faults completed on turbine Y at functional location “… – GBX”. However, the major issue with this approach is the size of the resulting data set. In data obtained from a major wind farm owner and operator, almost no cases exist where such a like-for-like comparison can be made, mostly due to inherently high availability of certain turbine models.

To combat this issue, two distinct approaches could be used. On one hand, to find similar faults, generalizations on functional locations and/ or turbines must be made. On the other hand, to find more faults on the same functional locations and/ or turbines, generalizations on faults must be made. To alleviate the issue of the resultant size of the data set and compare similar faults, a compromise is proposed. To increase the sample size of relevant work orders when calculating metrics, the hierarchical grouping strategy in Table 1 evaluated:

In this strategy, work orders are first, categorized by their order type and second, grouped into their turbine specific functional locations. By this method, only work orders of the same order type in the same functional location will be compared with one another.

Table 1: Work Order Grouping Strategy

1st Level	2nd Level
Order Type	Functional Location
ZPM0/6 Large Corrective/ Refurbishment/ Improvement	ELE Electrical
ZPM1 Reactive Maintenance	FAC Structures and Facilities
ZPM2/4 Predictive Maintenance/ Inspections	FND Foundation
ZPM3 Preventative Maintenance	GBX Gearbox
ZPM5 Change Maintenance	GEN Generator
	HYD Hydraulic Units
	INS Instrumentation
	MCS Monitoring Communication Systems
	PCD Power Condition
	PTH Pitch System
	ROT Rotor
	XFR Transformer Center
	YAW Yaw System

A caveat must be mentioned relating to this work order grouping strategy. By aggregating all work orders at the lowest level to the functional location of a specific turbine, there is an inherent risk that work orders of a different fundamental nature will grouped together. To illustrate this potential, the following two work order grouping designations are extended to their maintenance activity type: ZPM1 → … – GBX – MAT100 and ZPM1 → … – GBX – MAT102. While the first work order is MAT100 (operational) and the second is MAT102 (electrical), they are of the same order type and are servicing the same functional location. In the proposed grouping strategy, these two work orders are treated equally, while in reality they are potentially servicing different elements of the same functional location. As they are fundamentally different types of work, an argument could be made that they should not be grouped together. However, through practical observation and calculation, the risk this scenario poses to the accurate calculation of performance metrics is deemed minimal.

By applying the proposed work order grouping strategy to data provided from a large wind farm owner and operator, sufficient sample sizes of relatively similar complexity and fundamentally related work orders are achieved for performance metric calculation. With a systematic work order grouping strategy, metrics can be calculated with relative confidence.

3.3 Work Order Filtering and Data Cleaning Strategy

In addition to creating an effective work order grouping strategy, an efficient data cleaning strategy must be established. Many of the issues that surround intuitive problem solving involving data can be sourced to the lack of consistent and accurate data structure, content, and logic. To create a repeatable process for performance metric generation, the following data cleaning strategy is proposed. The proposed process has been briefly described for the generic application in Table 2, as well as for the case study of a large wind farm owner and operator in Chapter 4.

Table 2: Work Order Filtering and Data Cleaning Strategy

General Process Step	Case Study Specific Steps
Data collection	SQL query & download of "Work Order Headers" database
	SQL query & download of "Notifications" database
	SQL query & download of "Work Order Operations" database
	Full join of databases on work order number (WO #)
Irrelevant data removal	Removal of irrelevant & duplicate data fields
	Removal of instances w/o designated WO #
	Removal of work orders w/o "Actual Hours Worked"
Re-formatting	Consistent formatting of remaining "Date" data fields
	Consistent formatting of remaining "Time" data fields
	Consistent formatting of remaining "Char" data fields
	Consistent formatting of remaining "Num" data fields
	Re-designation of "Order Type" to consistent format
Re-distribution	Re-distribution of general turbine work orders to individual functional locations
Filtering	Filter instances by region
	Filter instances by wind farm
	Filter instances by sub-wind farm
	Filter instances by turbine level work orders
	Filter instances by date range
Grouping	Grouping of individual operations to specific work order
	Final data field selection and ordering

Now that an effective work order grouping strategy and work order filtering and data cleaning strategy have been proposed, the derivation of individual work order level and technician level performance sub-metrics can be discussed. The following sections illustrate the methodology of calculation of historical technician performance sub-metrics and includes: 1) Declaration of common indices, 2) Performance sub-metrics by individual work order, and 3) Performance sub-metrics by technician.

3.4 Performance Sub-Metric Generation

3.4.1 Declaration of Common Indices

The following declares the common set of indices used in all derivations and calculations.

i ≡ ith technician in technician availability pool for task team assignment,
for $i = 1, 2, \ldots, I$

j ≡ jth order type of completed work order,
for $j = 1, 2, 3, 4, 5$, where
    1 ≡ ZPM0/6,
    2 ≡ ZPM1,
    3 ≡ ZPM2/4,
    4 ≡ ZPM3, and
    5 ≡ ZPM5

k ≡ kth attribute type calculated from completed work order,
for $k = 1, 2, 3, 4, 5, 6$, where
    1 ≡ Quality (Q),
    2 ≡ Timeliness (T),
    3 ≡ Efficiency (E),
    4 ≡ Documentation (D),
    5 ≡ Task Completion Rate (TCR), and
    6 ≡ Task-Based Certification (TCR)

m ≡ mth metric of the kth attribute type calculated for completed work order of jth order type,
for $m = 1, 2, \ldots, M_{jk}$

n ≡ nth work order completed by ith technician in jth order type,
for $n = 1, 2, \ldots, N_{ij}$

3.4.2 Performance Sub-Metrics by Individual Work Order

Quality, Timeliness, Efficiency, and Documentation performance sub-metrics are calculated for each individual work order. These metrics are awarded to each technician who worked on the team that completed that respective work order. Full mathematical descriptions, colloquial descriptions, examples, ranges, targets, and notes are given in Appendices B.3 for Quality (k = 1), B.4 for Timeliness (k = 2), B.5 for Efficiency (k = 3), and B.6 for Documentation (k = 4).

Performance sub-metrics for individual work orders use the consistent form, k_{ij}^{mn}, where i is the i^{th} technician, j is the j^{th} work order type, k is the k^{th} attribute, m is m^{th} performance sub-metric of the k^{th} attribute and j^{th} order type, and n is the n^{th} work order, as notated in the declaration of common indices. Performance sub-metrics for individual work orders include: $Q_{ij}^{1n}(Th_1)$, $Q_{ij}^{1n}(Th_2)$, $Q_{ij}^{1n}(Th_3)$, $Q_{ij}^{1n}(Th_4)$, $Q_{ij}^{1n}(Th_5)$, $Q_{ij}^{1n}(Th_6)$, $Q_{ij}^{1n}(Th_7)$, Q_{i4}^{2n}, T_{ij}^{1n}, T_{ij}^{2n}, T_{ij}^{3n}, T_{ij}^{4n}, E_{ij}^{1n}, E_{ij}^{2n}, E_{ij}^{3n}, E_{ij}^{4n}, E_{ij}^{5n}, E_{ij}^{6n}, E_{ij}^{7n}, D_{ij}^{1n}, D_{ij}^{2n}, and D_{ij}^{3n}, where Th is the threshold by which the Q_{ij}^{1n} of a work order is compared against, as discussed in the notes of Table 7 in Appendix B.3.

Summarized information is not shown for performance sub-metrics for individual work orders. Instead, Table 3 summarizes all aggregated performance sub-metrics over their respective N_{ij} work orders. Detailed descriptions, units, ranges, and targets of the aggregated performance sub-metrics are identical to their respective individual work order performance sub-metrics.

3.4.3 Performance Sub-Metrics by Technician

The Quality, Timeliness, Efficiency, and Documentation performance sub-metrics calculated for each individual work order are aggregated to those technicians on the teams that completed them. Work order performance sub-metrics are averaged over the specific order types, as outlined in the previously mentioned Work Order Grouping Strategy. Therefore, each technician that has completed an evaluated work order can potentially have all previously mentioned performance sub-metrics, averaged over each j = 1, 2, 3, 4, and 5, respectively, provided data exists.

Additionally, technician level metrics, Task Completion Rate and Task-Based Certification, are calculated for each technician. Full mathematical descriptions, colloquial descriptions, examples, ranges, targets, and notes are given in Appendices B.7 for Task Completion Rate (k = 5) and B.8 for Task-Based Certification (k = 6).

Table 3, given for reference, details all performance sub-metrics aggregated over all work orders and grouped by technician, provided data exists. Aggregated performance sub-metrics use the consistent form, k_{ij}^{m}, where i is the i^{th} technician, and j is the j^{th} work order type, k is the k^{th} attribute, and m is m^{th} performance sub-metric of the k^{th} attribute and j^{th} order type, as notated in the declaration of common indices. The n^{th} work order designation is no longer needed as these sub-metrics represent the aggregation over N_{ij} work orders, as discussed in Section 3.5.1.

Table 3: Aggregated Performance Sub-Metrics

Metric	Sub-Metric	Description	Units	Range	Target
k = 1	$Q_{ij}^{1}(Th_1)$	Performance against threshold (Th) 1	–	[0, 1]	1
	$Q_{ij}^{1}(Th_2)$	Performance against threshold (Th) 2	–	[0, 1]	1
	$Q_{ij}^{1}(Th_3)$	Performance against threshold (Th) 3	–	[0, 1]	1
	$Q_{ij}^{1}(Th_4)$	Performance against threshold (Th) 4	–	[0, 1]	1
	$Q_{ij}^{1}(Th_5)$	Performance against threshold (Th) 5	–	[0, 1]	1
	$Q_{ij}^{1}(Th_6)$	Performance against threshold (Th) 6	–	[0, 1]	1
	$Q_{ij}^{1}(Th_7)$	Performance against threshold (Th) 7	–	[0, 1]	1
	Q_{ij}^{2}	Events between services (j = 4)	Events	{0, 1, … }	0
k = 2	T_{ij}^{1}	Hours worked – operational	Hours	[0, ∞]	Min
	T_{ij}^{2}	Finish date/ time vs deadline	Hours	[-∞, ∞]	Max
	T_{ij}^{3}	Hours worked – SAP	Hours	[0, ∞]	Min
	T_{ij}^{4}	Operational vs SAP hours worked	Hours	[0, ∞]	0
k = 3	E_{ij}^{1}	Operational hours dedicated to SPD	Hours	[0, ∞]	Min
	E_{ij}^{2}	Operational hours dedicated to T	Hours	[0, ∞]	Min
	E_{ij}^{3}	Operational hours dedicated to TIS	Hours	[0, ∞]	Max
	E_{ij}^{4}	Operational hours dedicated to R1	Hours	[0, ∞]	Max
	E_{ij}^{5}	Operational hours dedicated to R2	Hours	[0, ∞]	Max
	E_{ij}^{6}	Indirect to direct operational hours worked	–	[0, ∞]	Min
	E_{ij}^{7}	Actual hours to expected hours worked	–	[0, ∞]	Min
k = 4	D_{ij}^{1}	Missing data in documentation	–	[0, 1]	0
	D_{ij}^{2}	Logical inconsistency in documentation	–	[0, 1]	0
	D_{ij}^{3}	Wrong data input in documentation	–	[0, 1]	0
k = 5	TCR_{ij}^{1}	Number of completed tasks	Tasks	{0, 1, …}	Max
	TCR_{ij}^{2}	Number of completed tasks in last 1 year	Tasks	{0, 1, …}	Max
k = 6	TBC_{ij}^{1}	Completion % of certification level 1	%	[0, 1]	1
	TBC_{ij}^{2}	Completion % of certification level 2	%	[0, 1]	1
	TBC_{ij}^{3}	Completion % of certification level 3	%	[0, 1]	1

3.5 Technician Proficiency Matrix

After performance sub-metrics for individual work orders and for technicians have been calculated, they must be aggregated. Through aggregation, the kth performance metric for the jth order type for the ith technician can be calculated and used to inform future decisions by way of the Technician Proficiency Matrix. The following are the general steps in aggregating the previously mentioned performance sub-metrics to their respective kth performance metric.

3.5.1 Performance Sub-Metric Aggregation

All calculated performance sub-metrics for each individual work order were grouped by the ith technician and the jth order type. The average of each performance sub-metric was then found over all individual work order performance sub-metrics. This process is illustrated below for $Q_{ij}^{1}(Th_1)$:

$$Q_{ij}^{1}(Th_1) = \frac{1}{N_{ij}} \sum_{n=1}^{N_{ij}} Q_{ij}^{1n}(Th_1)$$

for i = 1, 2, … I and j = 1, 2, 3, 4, and 5, where N_{ij} is the number of work orders the ith technician completed in the jth order type for which $Q_{ij}^{1n}(Th_1)$ was finite.

This process was completed to find the following aggregated performance sub-metrics: $Q_{ij}^{1}(Th_1)$, $Q_{ij}^{1}(Th_2)$, $Q_{ij}^{1}(Th_3)$, $Q_{ij}^{1}(Th_4)$, $Q_{ij}^{1}(Th_5)$, $Q_{ij}^{1}(Th_6)$, $Q_{ij}^{1}(Th_7)$, Q_{i4}^{2}, T_{ij}^{1}, T_{ij}^{2}, T_{ij}^{3}, T_{ij}^{4}, E_{ij}^{1}, E_{ij}^{2}, E_{ij}^{3}, E_{ij}^{4}, E_{ij}^{5}, E_{ij}^{6}, E_{ij}^{7}, D_{ij}^{1}, D_{ij}^{2}, and D_{ij}^{3}. Additionally, by definition, TCR_{ij}^{1}, TCR_{ij}^{2}, TBC_{ij}^{1}, TBC_{ij}^{2}, and TBC_{ij}^{3} are already effectively aggregated over the jth order type for the ith technician.

3.5.2 Quality Profile (QP_{ij}) and Q^{1}_{ij}

As noted in Table 7 in Appendix B.3 when discussing the formulation of Q^{1n}_{ij}, evaluation was conducted over multiple thresholds (Th):

$$Th = [0 \;\; 30 \;\; 60 \;\; 90 \;\; 120 \;\; 150 \;\; 180] \text{ days}$$

where 180 days was chosen as the maximum Th because that is the typical interval between ZPM3 (preventative maintenance). This approach yielded $Q^{1n}_{ij}(Th_1)$, $Q^{1n}_{ij}(Th_2)$, $Q^{1n}_{ij}(Th_3)$, $Q^{1n}_{ij}(Th_4)$, $Q^{1n}_{ij}(Th_5)$, $Q^{1n}_{ij}(Th_6)$, and $Q^{1n}_{ij}(Th_7)$ at the individual work order level.

After aggregating over all work orders in the j^th order type for the i^th technician to achieve $Q^{1}_{ij}(Th_1)$, $Q^{1}_{ij}(Th_2)$, $Q^{1}_{ij}(Th_3)$, $Q^{1}_{ij}(Th_4)$, $Q^{1}_{ij}(Th_5)$, $Q^{1}_{ij}(Th_6)$, and $Q^{1}_{ij}(Th_7)$, it is important to generate the technician Quality Profile (QP_{ij}) and Q^{1}_{ij}. The QP_{ij} is the profile generated when the Q^{1}_{ij} at individual thresholds are connected and illustrates how a technician's quality of a completed job changes with time. The Q^{1}_{ij} is the area under the curve of the QP_{ij}. The area under the curve is calculated through simple trapezoidal integration. This is illustrated in Figure 5.

In addition to its use in generating Q^{1}_{ij} using the area under the curve, the QP_{ij} has added practical use as a potential tool for technician performance evaluation. A performance manager could directly use the QP_{ij} to compare the lasting quality of two or more technicians and draw useful insights from the relative shape comparisons of the profiles. Information could be attained that might be masked when the area under the curve is taken to generate Q^1_{ij}. As such, in addition to the generation of Q^1_{ij}, it is recommended to take note of the availability of the QP_{ij} for the i^{th} technician in the j^{th} order type.

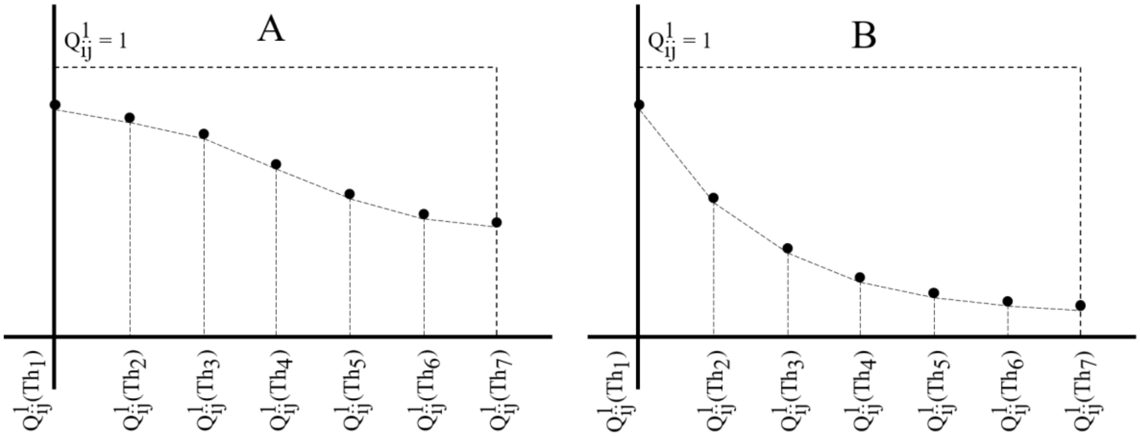


Figure 5: Quality Profile of Technicians A and B

3.5.3 Normalization

To compare different technicians using performance sub-metrics and metrics, normalization over all documented technicians must occur. This enables a relative comparison to the mean of the technician group to be created for each individual technician.

Normalization is often preferred for two main reasons. The first reason is that it is usually more beneficial to evaluate technicians relative to their peers rather than a potentially subjective absolute benchmark. Through normalization, the best technician will become the benchmark for performance evaluation. This enables a dynamic benchmark which evolves with changes to technician skills or technician pool composition. The second reason is that normalization has the benefit of scaling all sub-metrics to a standard normal distribution, N(0,1). As all sub-metrics now follow the same distribution, they are easily added together to create their respective k^{th} performance metric used in the Technician Proficiency Matrix. Without this scaling effect, addition in this way would not be possible.

Each sub-metric mentioned previously is normalized over the documented technician pool. The technician pool average and standard deviation is found for each sub-metric and the following formula, illustrated with the Q_{ij}^{1} sub-metric, is applied to normalize the i^{th} technician's aggregated sub-metric for the j^{th} order type:

$$Q_{ij}^{1} = \frac{Q_{ij}^{1} \text{ - Ave}}{\text{St. Dev.}} \sim N(0,1)$$

A final note on normalization is with respect to the direction of improvement for each documented sub-metric. If the sub-metric direction of improvement is (+), then the normalization formula mentioned above is sufficient. However, if the sub-metric direction of improvement is (–), then the resulting normalized performance sub-metric must be multiplied by (–1), essentially changing the direction of improvement to (+). This ensures that when all sub-metrics are combined, they all represent the same direction of improvement. Table 4 illustrates the direction of improvement for each sub-metric.

Table 4: Performance Sub-Metric Direction of Improvement

Sub-Metric	Direction of Improvement	Normalized Metric Multiplied by (–1)
Q_{ij}^{1}	+	NO
Q_{i4}^{2}	–	YES
T_{ij}^{1}	–	YES
T_{ij}^{2}	+	NO
T_{ij}^{3}	–	YES
T_{ij}^{4}	–	YES
E_{ij}^{1}	–	YES
E_{ij}^{2}	–	YES
E_{ij}^{3}	+	NO
E_{ij}^{4}	+	NO
E_{ij}^{5}	+	NO
E_{ij}^{6}	–	YES
E_{ij}^{7}	–	YES
D_{ij}^{1}	–	YES
D_{ij}^{2}	–	YES
D_{ij}^{3}	–	YES
TCR_{ij}^{1}	+	NO
TCR_{ij}^{2}	+	NO
TBC_{ij}^{1}	+	NO
TBC_{ij}^{2}	+	NO
TBC_{ij}^{3}	+	NO

3.5.4 Weighted Average

The final calculation to the normalized sub-metrics to create the respective k^{th} performance metric is an application of weighted averaging. Each group of sub-metrics is given a set of parameters for coefficients. These coefficients must sum to 1 for each group of sub-metrics. The parameter sets are as follows:

<u>k = 1:</u> q_{ij}^{m} for i = 1, 2, …, I, j = 1, 2, 3, 4, and 5, and m = 1 and 2, where
$\sum_{m=1}^{1} q_{ij}^{m} = 1$ for j = 1, 2, 3, and 5, and
$\sum_{m=1}^{2} q_{ij}^{m} = 1$ for j = 4

<u>k = 2:</u> t_{ij}^{m} for i = 1, 2, …, I, j = 1, 2, 3, 4, and 5, and m = 1, 2, 3 and 4, where
$\sum_{m=1}^{4} t_{ij}^{m} = 1$ for all j

<u>k = 3:</u> e_{ij}^{m} for i = 1, 2, …, I, j = 1, 2, 3, 4, and 5, and m = 1, 2, 3, 4, 5, 6, and 7, where
$\sum_{m=1}^{7} e_{ij}^{m} = 1$ for all j

<u>k = 4:</u> d_{ij}^{m} for i = 1, 2, …, I, j = 1, 2, 3, 4, and 5, and m = 1, 2, and 3, where
$\sum_{m=1}^{3} d_{ij}^{m} = 1$ for all j

<u>k = 5:</u> tcr_{ij}^{m} for i = 1, 2, …, I, j = 1, 2, 3, 4, and 5, and m = 1 and 2, where
$\sum_{m=1}^{2} tcr_{ij}^{m} = 1$ for all j

<u>k = 6:</u> $tbc_{ij}^{m}$for i = 1, 2, …, I, j = 1, 2, 3, 4, and 5, and m = 1, 2, and 3, where
$\sum_{m=1}^{3} tbc_{ij}^{m} = 1$ for all j

Therefore, the final performance metrics, A_{ijk}, for i = 1, 2, …, I, j = 1, 2, 3, 4, and 5, and k = 1, 2, 3, 4, 5, and 6, are calculated as in Table 5.

In all applications of weighted averaging thus far, all weights within a sub-metric group have been equal. It is at the discretion of the operations director to set the weights. While equal weights may be a standard starting point, it is recognized that domain knowledge will likely allow specific manipulation of these weights to different values, provided they sum to 1 within the sub-metric group. More information on how to incorporate domain knowledge and preference weighting is contained in Section 5.2 and Appendix D.2 and D.2.1.

Table 5: kth Performance Metric Calculation

Performance Metric	Calculation	Applicable j
A_{ij1}	$q_{ij}^{1}Q_{ij}^{1}$	j = 1, 2, 3, and 5
A_{i41}	$\sum_{m=1}^{2} q_{ij}^{m}Q_{ij}^{m}$	j = 4
A_{ij2}	$\sum_{m=1}^{4} t_{ij}^{m}T_{ij}^{m}$	j = 1, 2, 3, 4, and 5
A_{ij3}	$\sum_{m=1}^{7} e_{ij}^{m}E_{ij}^{m}$	j = 1, 2, 3, 4, and 5
A_{ij4}	$\sum_{m=1}^{3} d_{ij}^{m}D_{ij}^{m}$	j = 1, 2, 3, 4, and 5
A_{ij5}	$\sum_{m=1}^{2} tcr_{ij}^{m}TCR_{ij}^{m}$	j = 1, 2, 3, 4, and 5
A_{ij6}	$\sum_{m=1}^{3} tbc_{ij}^{m}TBC_{ij}^{m}$	j = 1, 2, 3, 4, and 5

3.5.5 Technician Proficiency Matrix

Once all calculations have been completed, the resulting performance metrics, of the form A_{ijk}, are able to be used. A_{ijk} represents the ith technician's historical performance in the kth attribute and jth order type, relative to their peers.

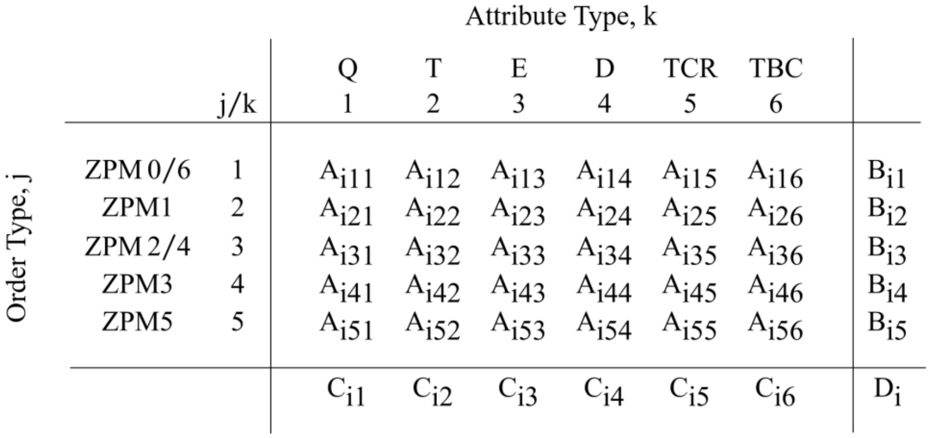
To gain clearer insight to a technician's performance in a certain order type or in a certain attribute type, aggregation of the A_{ijk} of the specific jth order type or kth attribute type can be completed. While there are many different aggregation methods that can be used, such as data envelopment analysis or work order type frequency weighting, simple averaging has been proposed as a simple illustration of principle. Alternative aggregation methods are discussed in Section 5.2 and Appendix D.2 and D.2.1.

Averaging A_{ijk} over the jth order type has been designated as the technician work order proficiency, B_{ij}. Averaging over the kth attribute type has been designated as the technician attribute proficiency, C_{ik}. It is noted that, in the proposed case study, equal weighting of all A_{ijk} coefficients, a_{ijk}, is used in the calculation of each B_{ij} and C_{ik}.

Finally, again using simple averaging for illustration purposes, either group of proficiencies can be averaged to create the overall technician proficiency, D_i. For this case study, it is noted that equal weighting of all B_{ij} and C_{ik} coefficients, b_{ij} and c_{ik}, respectively, is used in the calculation of D_i. With simple, non-weighted averaging, $\frac{1}{6}\sum_{k=1}^{6} C_{ik} = \frac{1}{5}\sum_{j=1}^{5} B_{ij}$, but, if weights were applied to specific B_{ij} or C_{ik}, then this relation would likely not hold.

With the basic technician performance metrics, A_{ijk}, the different technician proficiencies, B_{ij} and C_{ik}, and the overall technician proficiency, D_i, the Technician Proficiency Matrix can be created, as seen in Figure 6.

With creation of the Technician Proficiency Matrix, many different analyses can be conducted. Individual technician performance metrics can be evaluated or compared with other available technicians. A technician's j^{th} work order proficiency could be compared to their $(j+1)^{th}$ work order proficiency. A technician's k^{th} attribute in the j^{th} order type could be drilled down into sub-metrics to determine underlying trends. A single k^{th} attribute could be compared across all documented technicians. All technicians could be evaluated on their overall technician proficiency as a site-wide proficiency check. The possibilities are nearly limitless.



Attribute Type, k

Order Type, j	j/k	Q 1	T 2	E 3	D 4	TCR 5	TBC 6	
ZPM 0/6	1	A_{i11}	A_{i12}	A_{i13}	A_{i14}	A_{i15}	A_{i16}	B_{i1}
ZPM1	2	A_{i21}	A_{i22}	A_{i23}	A_{i24}	A_{i25}	A_{i26}	B_{i2}
ZPM 2/4	3	A_{i31}	A_{i32}	A_{i33}	A_{i34}	A_{i35}	A_{i36}	B_{i3}
ZPM3	4	A_{i41}	A_{i42}	A_{i43}	A_{i44}	A_{i45}	A_{i46}	B_{i4}
ZPM5	5	A_{i51}	A_{i52}	A_{i53}	A_{i54}	A_{i55}	A_{i56}	B_{i5}
		C_{i1}	C_{i2}	C_{i3}	C_{i4}	C_{i5}	C_{i6}	D_i

Figure 6: Technician Proficiency Matrix

From start to finish, the methodology to establish the holistic framework for generation of the Technician Proficiency Matrix has provided the following results:

1. Expert survey
2. Work order grouping strategy
3. Work order filtering and data cleaning strategy
4. Performance sub-metrics
5. Technician Proficiency Matrix

The uses for each piece of information individually and for all pieces holistically are varied and numerous. To illustrate some of these uses, Chapter 4 details a completed case study of a large wind farm owner and operator. Potential inferences that can be made from the results of the holistic Technician Proficiency Matrix framework are discussed.

4. CASE STUDY

The following case study of a large wind farm owner and operator details the holistic generation of the Technician Proficiency Matrix for a sub-farm with 10 technicians. Once generated, three (3) different use cases detailing various inferences will be explained and discussed. The analysis of each distinct case uses all assumptions previously mentioned, as referenced in Figure 19 in Appendix C.1, with random seed 0 for the basic illustration of the case study and random seeds 1, 37, and 48 for use cases 1, 2, and 3, respectively.

Three important items must be discussed regarding the case study. Notes 1 – 3 are briefly defined below and then discussed in detail in Appendix C.2.1, C.2.2, and C.2.3, respectively:

1. The large wind farm owner and operator does not currently record the individual technicians assigned to each work order. Technicians must be randomly generated.
2. The large wind farm owner and operator does not currently have in place standard operation line item descriptions. Text search and pre-defined allocation distributions must be used.
3. The large wind farm owner and operator designated the date range of post – January 1, 2017 as the case study range.

Of the five steps outlined in Chapter 3, the case study borrows exactly the procedures and results from the expert survey and the work order grouping strategy. The Work order filtering and data cleaning strategy is defined more specifically below. For brevity, the generation of the individual work order performance sub-metrics is not discussed. The performance sub-metrics attained after aggregation and normalization are illustrated. The Technician Proficiency Matrix for each technician is defined for this case study. Finally, three (3) distinct use cases are illustrated with conclusions drawn.

4.1 Generation of Technician Proficiency Matrices

Table 6: Case Study - Work Order Filtering and Data Cleaning
Rows – resulting number of data frame rows and
Cols – resulting number of data frame columns

General Process Step	Case Study Specific Step	Rows	Cols
Data collection	SQL download of "Work Order Headers" DB	77890	50
	SQL download of "Notifications" DB	72506	40
	SQL download of "Work Order Operations" DB	103743	33
	Full join of databases on work order (WO) #	167389	111
Irrelevant data removal	Removal of irrelevant & duplicate data fields	167389	59
	Removal of instances w/o designated WO #	151877	59
Re-formatting	Formatting of remaining "Date" data fields	151877	59
	Formatting of remaining "Time" data fields	151877	59
	Formatting of remaining "Char" data fields	151877	59
	Formatting of remaining "Num" data fields	151877	59
Filtering	Filter by region, wind farm, wind sub-farm	10230	59
	Filter by turbine level work orders	7005	59
	Filter by date range, post – 01/01/2017	1973	59
Re-distribution	Re-distribution of general turbine work orders to ALL individual functional locations	9521	61
Re-formatting	Grouping of individual operations to specific work order	9521	61
	Final data field ordering	9521	61
Filtering	Removal of work orders w/o "Actual Hours Worked"	5895	61
Re-formatting	Re-designation of "Order Type" to consistent format	5895	61

As can be seen in Table 6, iterative data selection, reformatting, and filtering enables radical data dimension reduction. The overall data set has been reduced from an initial full join of 167389 different work order and notification operations, each with at most 111 distinct data fields, to 5895 work order operations over 537 total work orders, each with only the most critical data fields. After data has been cleaned, random technician assignment must be completed, per note 1, above. Using 10 technicians, randomly sampled in sets of three without replacement for each of the 537 work orders, the distribution of work orders in Figure 7 is achieved, using random seed 0 as an example. The cleaned data for the wind sub-farm can now be used to generate performance sub-metrics for quality, timeliness, efficiency, documentation, and task completion rate.

For brevity and simplicity, the calculation of individual work order performance sub-metrics is not detailed. Instead, the case study performance sub-metrics are shown below after aggregation over all individual work orders and normalized over all documented technicians. The performance sub-metrics detail Q_{ij}^{1} (after area under the QP_{ij} has been calculated), Q_{i4}^{2}, T_{ij}^{1}, T_{ij}^{2}, T_{ij}^{3}, T_{ij}^{4}, E_{ij}^{1}, E_{ij}^{2}, E_{ij}^{3}, E_{ij}^{4}, E_{ij}^{5}, E_{ij}^{6}, E_{ij}^{7}, D_{ij}^{1}, D_{ij}^{2}, D_{ij}^{3}, TCR_{ij}^{1} and TCR_{ij}^{2} for technicians 1 through 10 for order types ZPM0/6, ZPM1, ZPM2/4, and ZPM3. Three items must be noted, below:

- TBC_{ij}^{1}, TBC_{ij}^{2}, and TBC_{ij}^{3} are #N/A in the following calculation as the structure needed to calculate these metrics was not currently in place when the case study was executed.

- ZPM0/6 is #N/A for all performance sub-metrics for all technicians due to lack of applicable work orders. As can be seen from Figure 7, there was only one applicable ZPM0/6 work order, assigned to technicians 3, 4, and 5. Because of lack of data, i.e. less than 2 work orders for calculation, no performance sub-metrics could be calculated.
- As with ZPM0/6, ZPM5 is #N/A for all performance sub-metrics for all technicians due to lack of applicable work orders. As can be seen from Figure 7, there were no applicable ZPM5 work orders.

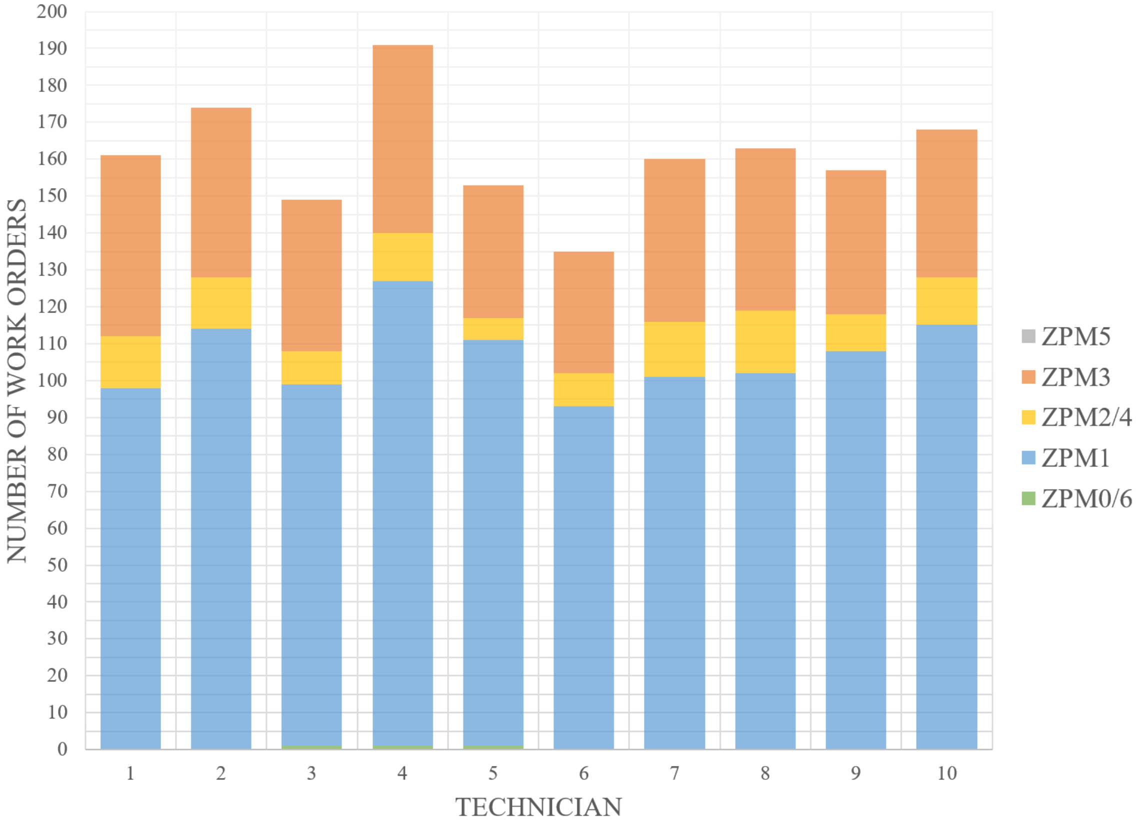
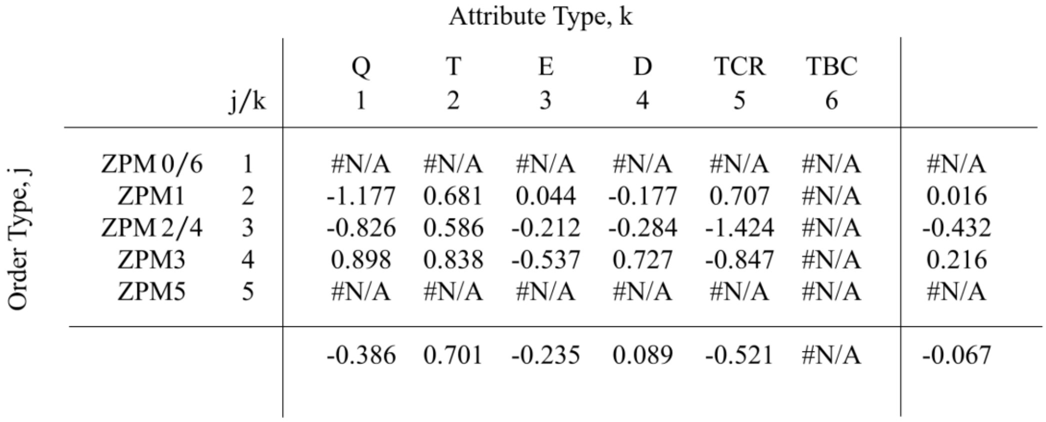


Figure 7: Technician Work Order Distribution by Order Type

All performance sub-metrics are aggregated over all work orders for each technician and have been normalized according to a N(0,1) distribution. Additionally, it can be seen that TBC^1_{ij}, TBC^2_{ij}, and TBC^3_{ij} are not calculated, ZPM0/6 is included for technicians 3, 4, and 5, but are #N/A for all performance sub-metrics, and no technician has a calculated performance sub-metric (including #N/A) registered for ZPM5. Aggregated and normalized performance sub-metrics for all technicians may be seen in Figure 20, in Appendix C.3.

Each performance sub-metric is aggregated through weighted average (equal weights in all cases for this case study) to create the respective kth performance metric in the jth order type for each technician, A_{ijk}. Additionally, performance metrics are aggregated through simple averaging to create the technician work order proficiencies, B_{ij}, technician attribute proficiencies, C_{ik}, and overall technician proficiencies, D_i. The final Technician Proficiency Matrix, using the example of the 5th technician, can be seen below:



			Attribute Type, k						
			Q	T	E	D	TCR	TBC	
		j/k	1	2	3	4	5	6	
Order Type, j	ZPM 0/6	1	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
	ZPM1	2	-1.177	0.681	0.044	-0.177	0.707	#N/A	0.016
	ZPM 2/4	3	-0.826	0.586	-0.212	-0.284	-1.424	#N/A	-0.432
	ZPM3	4	0.898	0.838	-0.537	0.727	-0.847	#N/A	0.216
	ZPM5	5	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
			-0.386	0.701	-0.235	0.089	-0.521	#N/A	-0.067

Figure 8: Technician Proficiency Matrix, Technician #5 (i = 5)

Graphics illustrating all technician performance metrics, A_{ijk} in Figure 21, work order proficiencies, B_{ij} in Figure 22, and attribute proficiencies, C_{ik} in Figure 23, may be viewed in Appendices C.4, C.5, and C.6, respectively. The i^{th} technician's overall proficiency, D_i, can also be seen on each graphic as the black points connected by a dashed line.

4.2 Use Cases

To illustrate different examples of the holistic generation of the Technician Proficiency Matrix, the following three use cases offer critical evaluation of distinct scenarios. In each case, the random seed for technician-to-work-order assignment was varied and the resulting scenarios were analyzed. Details drawn from the different use cases range from simple observations in some cases to complex inferences in other cases.

Therefore, all following use cases represent scenarios that initiate at the point where an operations manager has completed calculation of technician performance metrics, A_{ijk}, work order proficiencies, B_{ij}, attribute proficiencies, C_{ik}, and overall proficiencies, D_i. The operations manager, having evaluated all A_{ijk}, B_{ij}, C_{ik}, and D_i for technicians 1 through 10 over all work order and attribute types, inputs the raw data into a graphical template. From the graphical template, they can visually inspect relative technician performance against their peers and determine any interesting phenomena. The operations manager must now provide evaluation inferences to the operations director to potentially inform future decisions.

4.2.1 Use Case 1

In Use Case 1, random seed 1, the operations manager draws two important conclusions from the graphical representation of the technician performance metrics and overall proficiencies, A_{ijk} and D_i, in Figure 9: 1) Different compositions in individual technician performance metrics can yield similar overall proficiencies and 2) new hires can still perform comparatively well to their peers. This is illustrated through the following scenario.

The operations manager wants to provide a recommendation on how to improve the 7th technician's quality attribute proficiency as that of Technician 7 is significantly lower than that of other technicians. The operations manager sees that Technicians 1, 2, and 8 have the highest overall proficiency scores, which are all relatively similar. However, to choose which of the technicians to pair with the 7th technician, the operations manager evaluates the individual performance metrics and distributions of performance metrics for these technicians. They find the following:

- Technician 1 has an un-skewed distribution with an almost equal number of performance metrics better than or worse than their overall proficiency. Their quality attribute proficiency is relatively average.
- Technician 2 has a negatively skewed distribution mainly because of one quality performance metric radically worse than the average technician. Like Technician 1, the 2nd technician's quality attribute proficiency is relatively average.

- Technician 3 has a positively skewed distribution mainly because of one quality and one task completion rate performance metric radically better than the average technician. The 8th technician has a very high quality attribute proficiency.

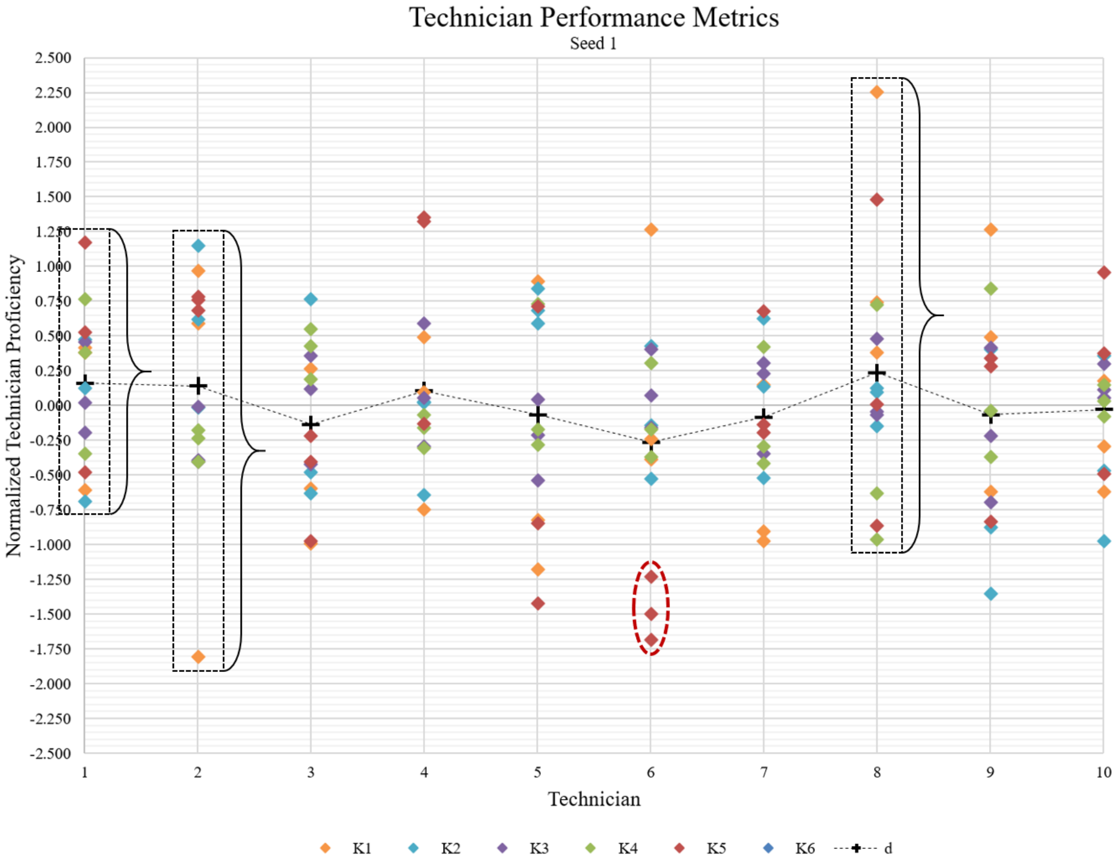


Figure 9: Technician Performance Metrics

From these observations, the operations manager clearly recognized that, although different technicians can have very different strengths and weaknesses, they can yield the same overall proficiencies. Therefore, to increase the quality attribute proficiency of the 7th technician, it was recommended they be paired with technician 8. Technician 8 was chosen as they have a high quality attribute proficiency. This is preferable to arbitrarily picking a technician among 1, 2, and 8 because they all share very similar overall proficiencies.

Additionally, the operations manager was asked to identify why Technician 6 has a lower overall proficiency than their peers. In evaluating individual performance metrics of the 6th technician, the operations manager identifies that the 6th technician must be either a new hire or a relatively inexperienced technician as they have a very low task completion rate attribute proficiency. Therefore, the operations manager can observe that, given the technician's inexperience, the technician is performing close to or better than their peers in most major attribute categories. In this case, it would be wise to monitor the inexperienced technician to determine if they continue to excel as they complete more tasks or if they regress back to the average technician's performance.

4.2.2 Use Case 2

In Use Case 2, random seed 37, the operations manager draws two important conclusions from the graphical representation of the technician work order proficiencies and overall proficiencies, B_{ij} and D_i, in Figure 10: 1) An individual technician can be extremely consistent across all work order types and 2) technician pools can be highly interchangeable. This is illustrated through the following scenario.

The operations manager has been tasked with determining whether Technician 2, who primarily completes ZPM2/4 work orders, can be reliably placed on teams handling

ZPM1 or ZPM3 work orders. The operations manager evaluates the individual work order proficiencies and their distributions and finds the following:

- Technician 2 is above the average technician's performance on all work order types
- Technician 2 has extremely consistent work order proficiency across all work order types, where data is present.

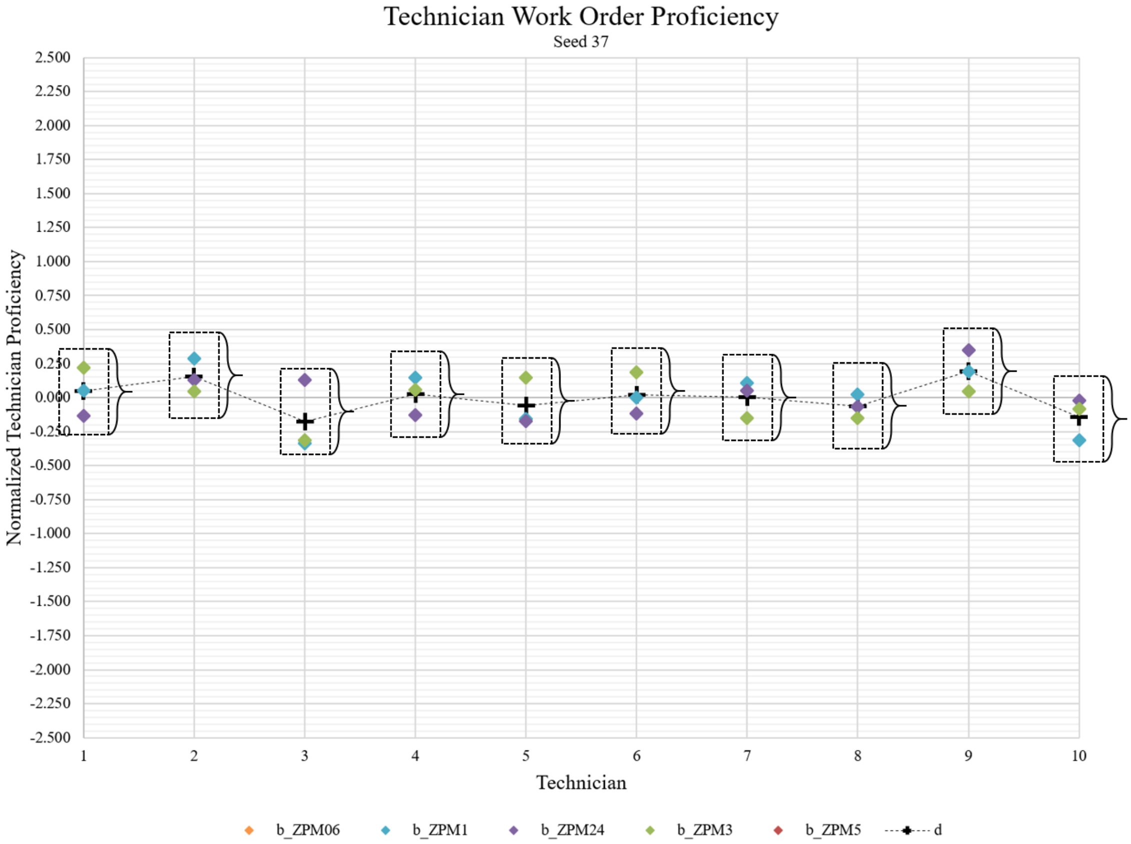


Figure 10: Technician Work Order Proficiency

From these conclusions, it is clear that the individual technician performs relatively well against the average technician with respect to all work order types. It is also clear that there is no significant difference in their individual performance across different work order types. Therefore, the operations manager can safely recommend that technician 2 may switch from ZPM2/4 work orders to either ZPM1 or ZPM3 work orders without a significant change in the performance outcome of the completed work order.

Additionally, the operations manager is asked to make a recommendation on which technicians may be considered interchangeable to this sub-farm. This is desired as this particular sub-farm experiences a low level of technician availability. Technicians are often pulled from this sub-farm to attend to complex tasks at other, less equipped farms. By evaluating the distribution of work order proficiencies of each technician and comparing them to each other, the operations manager makes the following conclusions:

- All technicians’ overall proficiencies are within 0.5 standard deviations of each other
- The range of all technicians’ work order proficiencies is less than 0.5 standard deviations

By these conclusions, all technicians are very close to one another in overall proficiencies and are consistent across multiple work order types. Therefore, the operations manager can safely recommend that almost any technician may be assigned to those tasks for which a regularly assigned technician is absent. This will result in a negligible difference to the overall outcome of the task completion in terms of performance metrics.

4.2.3 Use Case 3

In Use Case 3, random seed 48, the operations manager draws one important conclusion from the graphical representation of the technician performance metrics and overall proficiencies, A_{ijk} and D_i, in Figure 11: Both generalists and specialists can exist in the same pool of technicians. This is illustrated through the following scenario.

The operations manager has been tasked with defining a technician assignment strategy to build the capabilities of Technician 10. To do so, the operations manager is concerned with building capabilities by two methods: 1) Cross learning from specialists and 2) cross learning from generalists. With respect to specialty, Technician 10 needs assistance in the ZPM2/4 quality performance metric and in timeliness attribute proficiency. With respect to generality, Technician 10 needs a positive shift to overall proficiency.

For specialists, the operations manager is concerned with those technicians who have high proficiencies in the areas in which Technician 10 performs poorly. Pairing Technician 10 with a specialist will, theoretically, increase their performance metrics with respect to the specialized skill. For generalists, the operations manager is concerned with those technicians who have a very consistent distribution of performance metrics. Pairing Technician 10 with a generalist will, theoretically, holistically improve their overall set of performance metrics.

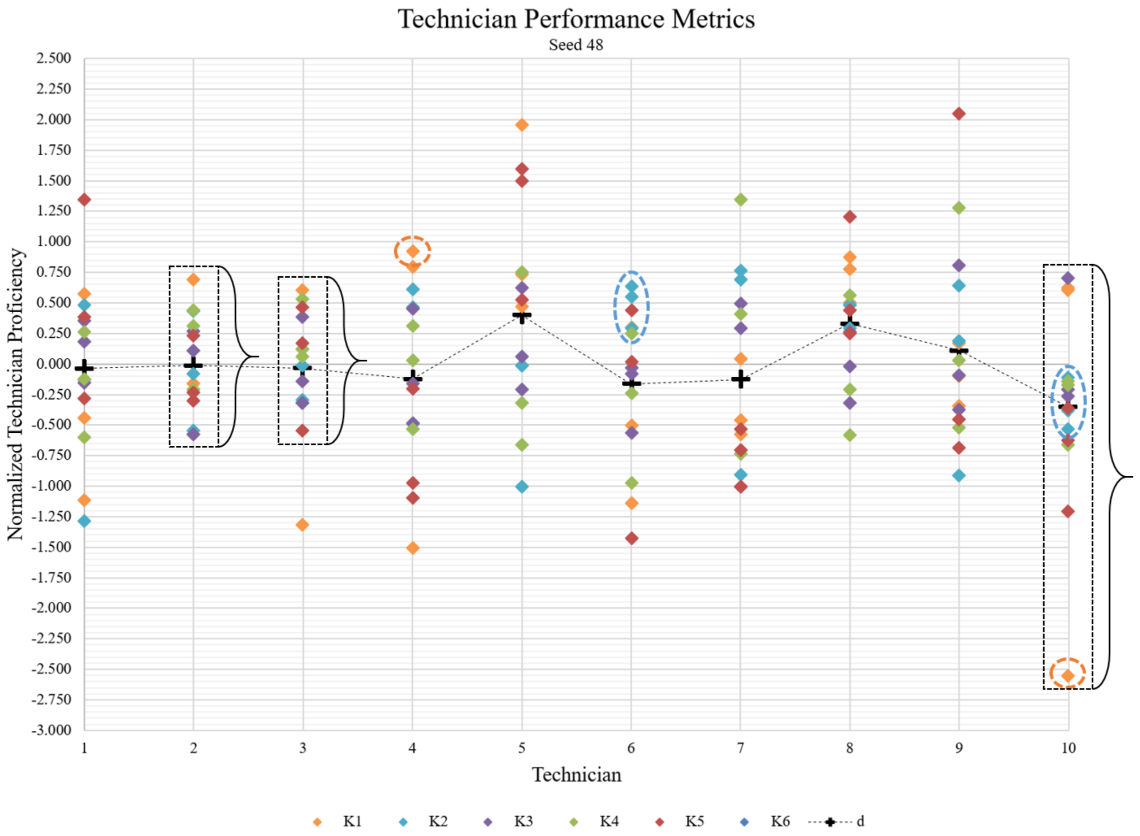


Figure 11: Technician Performance Metrics

The operations manager evaluates the individual performance metrics and respective distributions of all technicians and identifies the following conclusions:

- Technician 4 has the highest ZPM2/4 quality performance metric
- Technician 6 has the highest and most consistent timeliness attribute proficiency
- Technicians 2 and 3 have very consistent performance metrics across all work order and attribute types

Therefore, Technician 4 is labeled as a ZPM2/4 quality specialist, Technician 6 is labeled as a timeliness attribute proficiency specialist, and Technicians 2 and 3 are designated as generalists. Technician 4 is paired with Technician 10 on ZPM2/4 work orders as often as available to increase Technician 10’s ZPM2/4 quality performance metric. Technician 6 is paired with Technician 10 as often as available to increase Technician 10’s timeliness attribute proficiency. Technicians 2 and 3 are paired with Technician 10 as often as available to holistically improve and tighten the distribution of performance metrics of Technician 10.

5. DISCUSSION

In generating the framework for holistic performance metric generation, as detailed in the Chapter 3, and illustrated in Chapter 4, many observations were identified and refined. In the following sections, key insights derived from development of performance metrics and completion of the case study of a large wind farm owner and operator are discussed.

Briefly mentioned are recommendations on excellence in data quality, differing aggregation techniques for performance metrics and proficiencies, and a proposed integer programming modeling framework for task-to-team assignment. Expanded discussion and analysis for data quality, performance metric aggregation techniques, and integer programming modeling is contained within Appendices D.1, D.2, and D.3, respectively.

5.1 Excellence in Data Quality

In establishing a data-driven methodology for generation of technician performance metrics and proficiencies, four key elements of data quality were identified:

1. Consistent and accurate data entry (D.1.1)
2. Database consistency (D.1.2)
3. Technician recording (D.1.3)
4. Operation description consistency (D.1.4)

Consistent and accurate data entry must enable the user to consistently enter accurate information, enter information that matches the intended meaning of the data field, and avoid data entry mistakes due to confusion. Database consistency is concerned with design of appropriately similar and/ or dissimilar data fields across multiple databases to aid the user in inferring the intended meaning of specific data fields. Technician recording on individual work orders must be incorporated such that user input error is avoided. Finally, operation description consistency is required to simplify the calculation process of Efficiency and Documentation performance sub-metrics and eliminate the use of text-based searching methods and pre-defined work order hours allocation.

In developing robustness against these four data quality measures, the results of the individual Technician Proficiency Matrices will be more easily trusted and interpreted. Once robustness in data quality is achieved, strategic decisions may be confidently made upon the results of technician performance metrics and proficiencies.

5.2 Performance Metrics Aggregation Techniques

In calculating performance sub-metrics by work order and by technician, aggregated performance metrics, and attribute, work order, and overall technician proficiencies, there is ample opportunity to incorporate domain knowledge. This specific information may be included through the manipulation of different aggregation techniques. While there are advanced aggregation techniques such as data envelopment analysis and work order frequency weighting, these are considered out-of-scope for discussion. Therefore, the opportunity to affect change to the calculation of metrics and proficiencies is best realized through adjustment of calculation coefficients, i.e. simple weighting.

It is assumed that the discerning manager or executive will not want to manipulate results at such a granular level as the calculation of performance sub-metrics. Therefore, it is recommended that changing coefficient weights to represent domain knowledge be restricted to the calculation of technician performance metrics and proficiencies. The only caveat for changing calculation coefficients is that the sum of coefficients over the calculation must remain equal to 1. Further colloquial and mathematical explanations may be found in Appendix D.2 and D.2.1.

5.3 Task-to-Team Assignment Integer Programming Formulation

Once data-driven calculation of technician performance metrics and proficiencies has been completed, it becomes possible to construct an optimization program to assign technicians to pending maintenance tasks. However, when considering assignment, it is important to ensure that no one team suffers greatly for the benefit of another team in terms of overall performance metric or proficiency aggregates or scores. Therefore, it is proposed to use the maximin approach for the task-to-technician assignment integer program. Further exposition and assumptions, as well as the proposed model itself, is included in Appendix D.3 for elaboration.

When considering the task-to-team assignment integer program, certain scenarios must be considered for their impact:

1. Technician assignment restrictions and task prioritizations (D.3.3.1)
2. Basic certification requirements (D.3.3.2)
3. Work Order, Attribute, and Overall Proficiency Requirements (D.3.3.3)
4. Minimum Ability Spread Cross Learning and Assignment Mixing (D.3.3.4)
5. Emergency Planning & Manager Discretion (D.3.3.5)

Critical evaluation of these different scenarios for their impact to the assumptions, objectives, decision variables, and constraints of the proposed task-to-team assignment integer program, will yield a robust assignment model. Further, by incorporating the previous suggestions with regards to excellence in data quality and performance metrics aggregation techniques, the foundation for a holistic packaging of the Personnel Deployment Strategy may be achieved.

6. CONCLUSION

Throughout the course of this thesis, an extensive literature review was conducted, an extensive technician performance metric and proficiency generation methodology was defined, a thorough and in-depth case study was completed, and critical and expansive topics were provided and discussed.

In the literature review, the proposed research aims were critically evaluated against the thematic areas of performance measurement and management, maintenance modeling and management, reliability analysis, and team optimization. The proposed research direction was established as novel in the application of maintenance in the wind industry and an analysis of each major thematic area was conducted and expanded upon.

In the methodology, expansive processes and examples were detailed to establish the application independent development of the Technician Proficiency Matrix and associated information. Frameworks were identified and proposed for the incorporation of expert surveys, work order grouping strategies, and work order filtering and data cleaning strategies. Relationships were defined for calculation of technician performance sub-metrics and technician performance metric aggregation and normalization strategies were illustrated. Detailed explanation and development were provided for the creation of technician attribute, work order, and overall proficiencies with their potential uses highlighted. Finally, a framework was provided for conveniently locating all information in the Technician Proficiency Matrix.

In the case study of a large wind farm owner and operator, a detailed example of the holistic generation of the Technician Proficiency Matrices for a pool of technicians (randomly generated by uniform distribution without replacement, see Appendix C.2.1) was illustrated. Real work order data was provided over the entire life-span of all wind farms and wind sub-farms of the large wind farm owner and operator. This data was used to exemplify the creation of Technician Proficiency Matrices on a single wind sub-farm using work orders from January 1st, 2017 to March 15th, 2018. Three distinct use cases and resulting actions were presented through the perspective of an operations manager refining decisions for an operations director.

In the discussion of the different research aims of the Personnel Deployment Strategy, critical insights into proposals for excellent data quality were identified through development of the methodology and execution of the case study. Implementation strategies for consistent and accurate data entry, database consistency, technician recording, and operation description consistency were provided. A detailed explanation of the potential inclusion of domain knowledge and weighting preferences in performance metrics and proficiencies was offered. Finally, the proposed model for the task-to-team assignment integer program with critical consideration of specialty constraints and scenarios was offered.

As stated previously, the transition from a full-service (or hybrid) to a self-perform maintenance policy requires two major initiatives. The first, wholly transferring the skills and knowledge of the wind turbine original equipment manufacturer maintenance staff to the staff of the wind farm owner and operator, may be accomplished through strategic decision making, as illustrated in the use cases presented in Section 4.2. The second, efficient management and deployment of all operations and maintenance assets, may be accomplished through refinement and implementation of the task-to-team assignment integer programming formulation, as discussed in Section 5.3 and Appendix D.3. Holistically, the development of technician performance metrics and proficiencies, grouped with key insights into establishing excellent data quality practices and the proposal of a task-to-team assignment integer programming formulation, lays a firm foundation for facilitating a successful transition to a self-perform maintenance policy.

A critical belief in the continuing development of the Personnel Deployment Strategy is that a technician may distinguish themselves through their own performance. Yet, the question remains as to whether the capability to distinguish one's self stems from inherent ability or from opportunity. Are some technician's inherently better at certain tasks or is it strictly related to the developed experience through the opportunities afforded them? Can the performance of a technician who has little experience challenge that of those who have much? Certainly, it is possible to find concrete examples of both, inherent ability over experience and experience over inherent ability, which may sway methodology creation.

However, it is the personal choice of the author to assume a growth mindset and dictate that, no matter a technician's inherent ability, improvement is always a possibility through being afforded the opportunity to hone their skills. This is the thought process that is at the core of the Personnel Deployment Strategy, a chance to identify and decidedly help improve, in the most efficient manner, the abilities of every technician.

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APPENDIX A

EXPANSION OF LITERATURE REVIEW

As discussed by Levy and Ellis 2006 in their approach to a systematic literature review, “an effective literature review should include the following characteristics: a) methodologically analyze and synthesize quality literature, b) provide a firm foundation to a research topic, c) provide a firm foundation to the selection of research methodology, and d) demonstrate that the proposed research contributes something new to the overall body of knowledge or advances the research field’s knowledgebase.”[82] In this spirit, a systematic literature review has been completed to provide the bedrock for the development of a comprehensive research methodology for defining an optimal Personnel Deployment Strategy. The following appendices detail the individual steps conducted in this literature review.

A.1 Input

Input collection for the literature review includes four distinct, iterative search methods: 1) generic keyword search, 2) targeted keyword search, 3) publication citation search, and 4) author publication history search.

1. In the 1st round of the input stage, “generic keyword search”, three keywords were developed which were aligned with the proposed research direction: “performance measurement and management”, “team optimization”, and “deployment optimization”.
2. In the 2nd round of the input stage, key words were chosen from every relevant publication and reduced to create a set of targeted keywords.
3. In the 3rd round of the input stage, relevant citations were chosen from every publication selected from the 1st and 2nd round.
4. In the 4th and final round of the input stage, the entire publication history of every author sourced from the 1st, 2nd, and 3rd rounds of the input stage were reviewed.

*Initial key words were cross-referenced with “maintenance”, “wind”, and “wind farm” to trend search results, although no relevant results from other applications or industries were excluded

After completion of the four rounds of the input stage, a final cursory check against iteratively new keywords, citations, and authors was conducted to ensure no dramatic gaps in the comprehensiveness of the Relevant Body of Knowledge. While not every publication thematically relevant to the proposed research direction was recorded, a comprehensive picture of the state of the field was reached.

A.2 Processing

Themes were developed to compare the publications obtained in the input stage to the proposed research direction. The processing stage categorizes the publications according to the following themes:

Performance Measurement and Management (PM&M)

- Literature focused on understanding the importance of performance measurement and concerned with development of practical tools to adequately capture and manage it

Maintenance Modeling and Management (MMM)

- Literature focused on the development of optimized maintenance asset deployment strategies by leveraging reliability analysis and its predictions

Reliability Analysis (RA)

- Literature focused on the development of physics-based and data-driven modeling for turbine performance evaluation and fault detection

Team Optimization (TO)

- Literature focused on the development of optimization techniques and algorithms to yield the most optimal team composition for a specific application

Additionally, literature deemed relevant, but not adhering to one of the previous four themes was given the designation “Other” (OTH).

A.3 Output

The results shown in the output stage of the literature review contain two distinct items: 1) the Relevant Body of Knowledge with an overview of the resulting literature and 2) a thematic analysis.

A.4 Interpretation of the Relevant Body of Knowledge

- The first, second, and third circles represent hierarchical levels of thematic categorization for a publication, e.g. “PM&M” (1st) → “W” (2nd) → “M” (3rd)
- Lighter area coloring indicates publications are relevant to the author proposed research path while darker area colors indicate non-relevant publications
- The notation for the 3rd thematic categorization contains the number of publications existing in that thematic path, e.g. “RA” → “W” → “M 25” indicates 25 relevant publications in the maintenance function in the wind-industry w.r.t. Reliability Analysis
- A single publication may have multiple 1st level thematic categorizations, e.g. a publication may offer a fault prediction tool (Reliability Analysis) and recommend an optimized maintenance strategy (Maintenance Modeling and Management) based on the tool output
- Assuming an acceptably comprehensive literature search, missing and/ or small, lightly colored sections of the Relevant Body of Knowledge usually indicate an area where novel research may be applied

A.5 Thematic Groupings

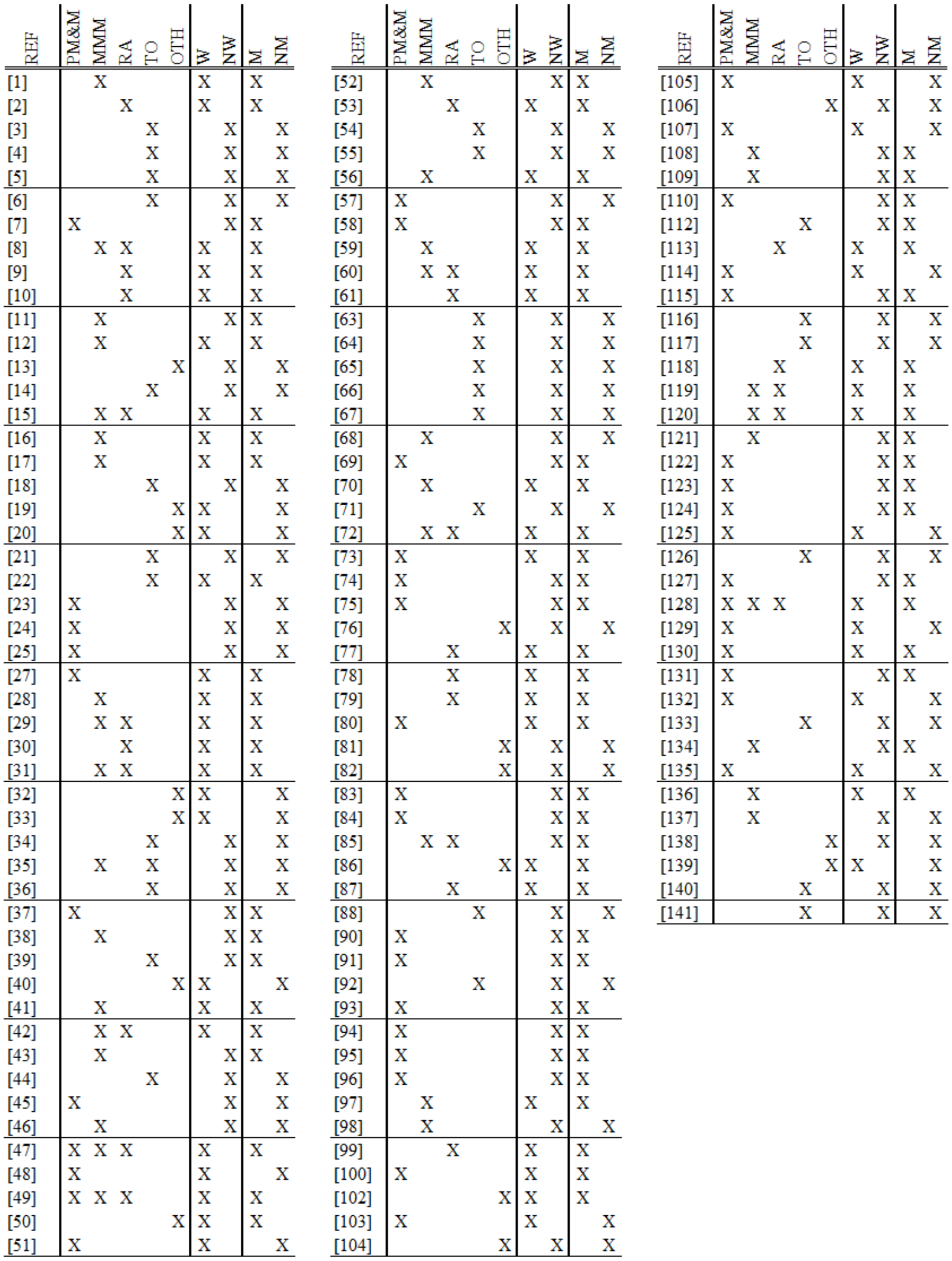

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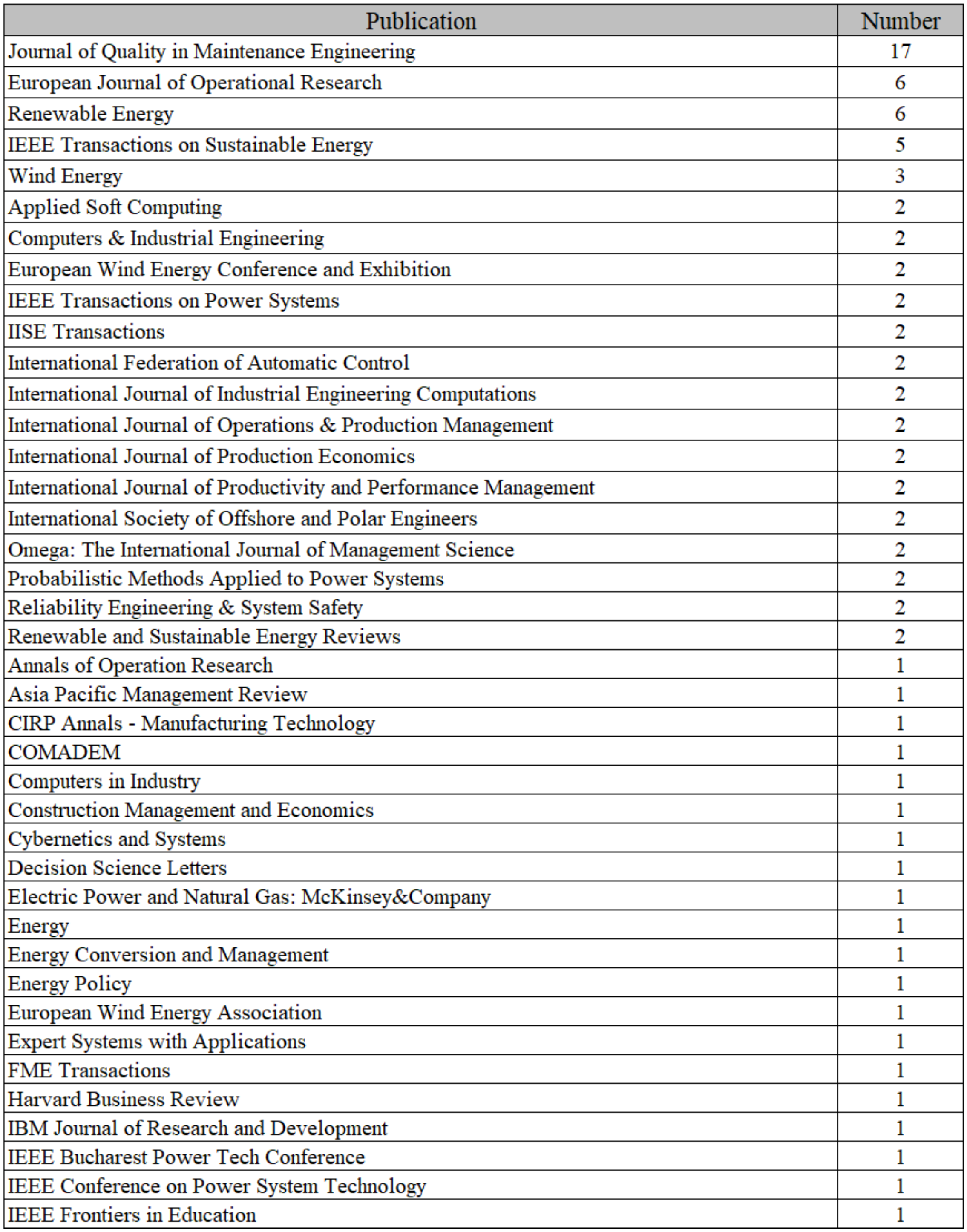
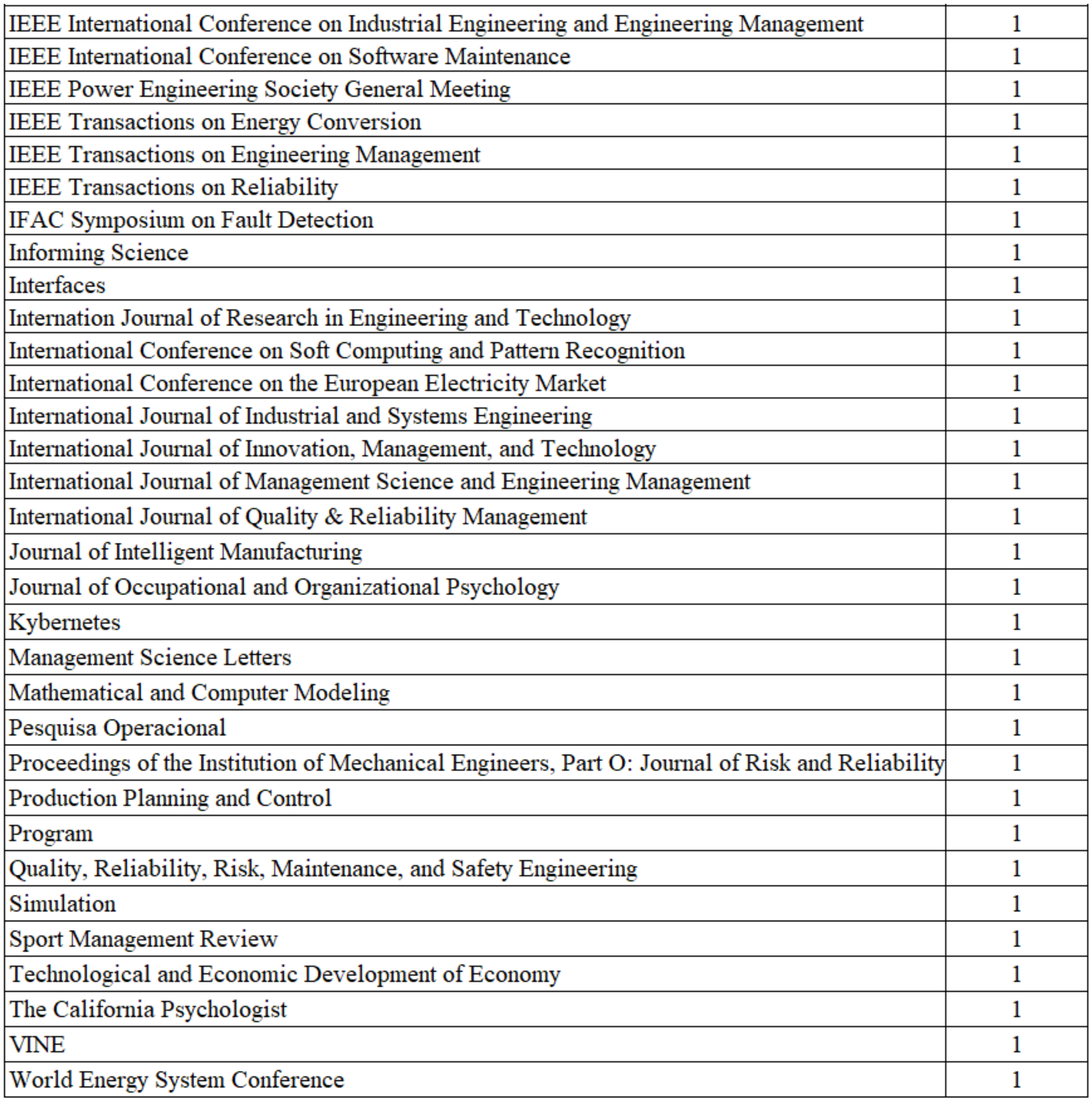
Figure 12: Thematic Grouping

A.6 Publications Referenced



Publication	Number
Journal of Quality in Maintenance Engineering	17
European Journal of Operational Research	6
Renewable Energy	6
IEEE Transactions on Sustainable Energy	5
Wind Energy	3
Applied Soft Computing	2
Computers & Industrial Engineering	2
European Wind Energy Conference and Exhibition	2
IEEE Transactions on Power Systems	2
IISE Transactions	2
International Federation of Automatic Control	2
International Journal of Industrial Engineering Computations	2
International Journal of Operations & Production Management	2
International Journal of Production Economics	2
International Journal of Productivity and Performance Management	2
International Society of Offshore and Polar Engineers	2
Omega: The International Journal of Management Science	2
Probabilistic Methods Applied to Power Systems	2
Reliability Engineering & System Safety	2
Renewable and Sustainable Energy Reviews	2
Annals of Operation Research	1
Asia Pacific Management Review	1
CIRP Annals - Manufacturing Technology	1
COMADEM	1
Computers in Industry	1
Construction Management and Economics	1
Cybernetics and Systems	1
Decision Science Letters	1
Electric Power and Natural Gas: McKinsey&Company	1
Energy	1
Energy Conversion and Management	1
Energy Policy	1
European Wind Energy Association	1
Expert Systems with Applications	1
FME Transactions	1
Harvard Business Review	1
IBM Journal of Research and Development	1
IEEE Bucharest Power Tech Conference	1
IEEE Conference on Power System Technology	1
IEEE Frontiers in Education	1

Figure 13: Referenced Publications



IEEE International Conference on Industrial Engineering and Engineering Management	1
IEEE International Conference on Software Maintenance	1
IEEE Power Engineering Society General Meeting	1
IEEE Transactions on Energy Conversion	1
IEEE Transactions on Engineering Management	1
IEEE Transactions on Reliability	1
IFAC Symposium on Fault Detection	1
Informing Science	1
Interfaces	1
Internation Journal of Research in Engineering and Technology	1
International Conference on Soft Computing and Pattern Recognition	1
International Conference on the European Electricity Market	1
International Journal of Industrial and Systems Engineering	1
International Journal of Innovation, Management, and Technology	1
International Journal of Management Science and Engineering Management	1
International Journal of Quality & Reliability Management	1
Journal of Intelligent Manufacturing	1
Journal of Occupational and Organizational Psychology	1
Kybernetes	1
Management Science Letters	1
Mathematical and Computer Modeling	1
Pesquisa Operacional	1
Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability	1
Production Planning and Control	1
Program	1
Quality, Reliability, Risk, Maintenance, and Safety Engineering	1
Simulation	1
Sport Management Review	1
Technological and Economic Development of Economy	1
The California Psychologist	1
VINE	1
World Energy System Conference	1

APPENDIX B

METHODOLOGY

B.1 Application Specific Nomenclature

Order Type:

“Order Type”, “Large Corrective”, “Refurbishment”, “Improvement”, “ZPM0/6”, “Reactive Maintenance”, ZPM1”, “Predictive Maintenance”, “Inspections”, “ZPM2/4”, “Preventative Maintenance”, “ZPM3”, “Change Maintenance”, “ZPM5”

Functional Location:

“Functional Location”, “Electrical”, “ELE”, “Structure and Facilities”, “FAC”, “Foundation”, “FND”, “Gearbox”, “GBX”, “Generator”, GEN”, “Hydraulic Units”, “HYD”, “Instrumentation”, “INS”, “Monitoring Communication Systems”, “MCS”, “Power Condition”, “PCD”, “Pitch System”, “PTH”, “Rotor”, “ROT”, “Transformer Center”, “XFR”, “Yaw System”, “YAW”

Databases:

“Work Order Headers”, “Notifications”, “Work Order Operations”, “Work Order Number”, “Actual Hours Worked”, “Order Type”

Data Fields:

“Actual Hours Worked”, “Malfunction End Date”, “Malfunction End Time”, “Actual Finish Date”, “Actual Finish Time”, “Actual Finish Execution Date”, “Actual Finish Execution Time”, “Basic Finish Date”, “Malfunction Start Date”, “Malfunction Start Time”, “Actual Start Date”, “Actual Start Time”, “Actual Start Execution Date”, “Actual Start Execution Time”, Basic Start Date”

B.2 Expert Survey Questions

1. What are the metrics by which you would rate a technician’s performance, given they were assigned
    a. a single task
    b. multiple tasks of the same turbine type, location, and weather conditions
    c. multiple tasks of differing severity, turbine type, location, and weather conditions
2. Are there other major potential variants that could affect a technician’s performance other than task severity, turbine type, turbine location, or weather conditions?
3. Are differences in skill expected to properly complete preventative vs reactive maintenance? i.e. should a technician be expected to perform each type of maintenance task equally well?
4. Are there major task types other than preventative and reactive maintenance?
5. Is there an effect on technician performance or productivity based on who his/ her teammates are? Who their team leader is? Who their site manager is?
6. Is proper safety procedure potentially hindering any previously mentioned performance metric? For example, does it take longer to complete a task when following proper safety procedures?
7. How, in a measurable way, can a technician champion safety? i.e. should there be a separate performance metric for safety or should it be assumed that all work is done with complete safety procedure adherence?

8. Is there variation in the task preparedness of each service center that would affect performance metrics? Should all service center preparedness be standardized?
9. Should proper work order documentation or completion be considered a performance metric? What additional work order fields would you consider to be most useful?
10. How do you think employee satisfaction plays a role in technician performance? How would you monitor technician satisfaction and how often? Are there any concerns from technicians that you are currently aware of?
11. What are the major levels of key performance indicator hierarchy that you are aware of? e.g. portfolio level, wind farm level, etc. Should we add any more under the change umbrella of self-perform?
12. Are there any other thoughts you have?

B.3 Quality (k = 1, Q) by Individual Work Order

To evaluate the quality associated with a work order (k = 1), two (2) distinct sub-metrics of form Q_{ij}^{mn} must be calculated for each work order. The calculation of the first sub-metric, Q_{ij}^{1n}, is not specific to any order type while that of the second, Q_{ij}^{2n}, is specific to order type ZPM3 (j = 4).

Q_{ij}^{1n}

Q_{ij}^{1n} is defined as the 1st quality sub-metric (m = 1) for the nth work order in the jth order type for the ith technician, for i = 1, 2, …, I, j = 1, 2, 3, 4, 5, and n = 1, 2, …, N_{ij}. Specifically, Q_{ij}^{1n} is the evaluation of the elapsed time (Δt) from documented close of the nth work order to the next immediate event in that specific work order grouping against 4 different cases, as summarized below:

Case 1 (Current Calculation)

The next immediate event is the date/ time associated with the performance metric calculation. As performance metric calculation was initiated before Δt could encounter another immediate event, no conclusion can be drawn about the quality of the nth work order in the work order group.

Case 2 (Threshold)

The next immediate event is the date/ time associated with a designated quality Threshold (Th) target. As Δt has reached or surpassed the associated Th, quality of the nth work order in the work order group has achieved the desired value.

Case 3 (ZPM0/6, ZPM1, ZPM2/4, or ZPM5)

The next immediate event is the date/ time associated with an occurring ZPM0/6, ZPM1, ZPM2/4, or ZPM5 work order. As Δt has not reached or surpassed the associated Th before the (n+1)th work order was triggered, quality of the nth work order in the work order group has not achieved the desired value.

Case 4 (ZPM3)

The next immediate event is the date/ time associated with an occurring ZPM3 work order. A ZPM3 (Preventative Maintenance) conceptually resets the specific functional location in which the nth work order occurred, rendering the quality evaluation inconclusive. As a ZPM3 has occurred before Δt could encounter another immediate event, no conclusion can be drawn about the quality of the nth work order in the work order group.

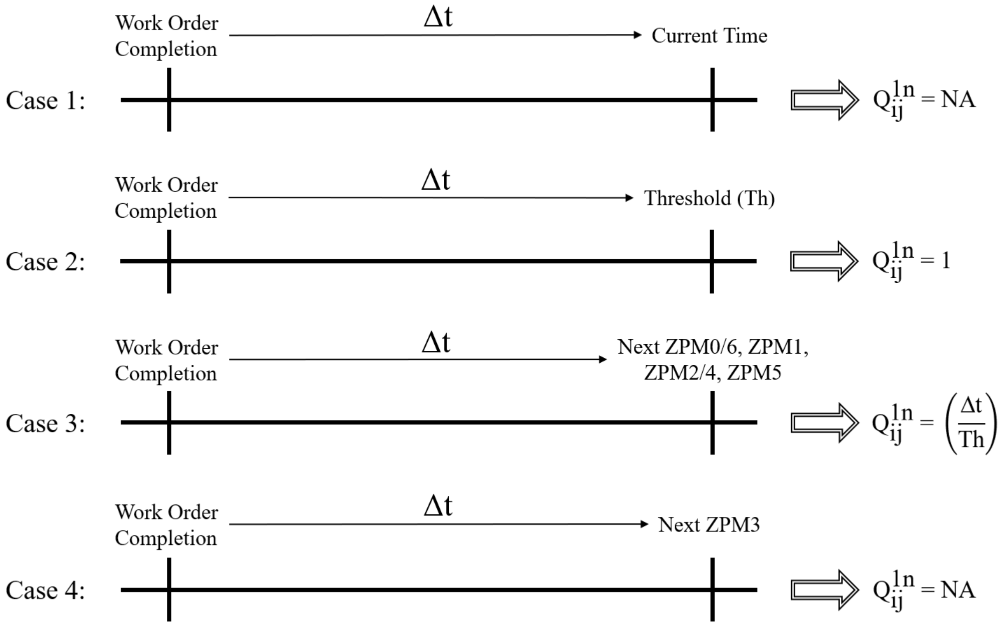


Figure 14: Visual Illustration, 1st Quality Sub-Metric

Q_{i4}^{2n}

Q_{i4}^{2n} is defined as the 2nd quality sub-metric (m = 2) for the nth work order in the 4th order type for the ith technician, for i = 1, 2, …, I, j = 4, and n = 1, 2, …, N_{i4}. Specifically, Q_{i4}^{2n} is the number of ZPM0/6, ZPM1, ZPM2/4, and ZPM5 work orders between the nth and (n+1)th work order of type j = 4 in the work order group, as illustrated below:

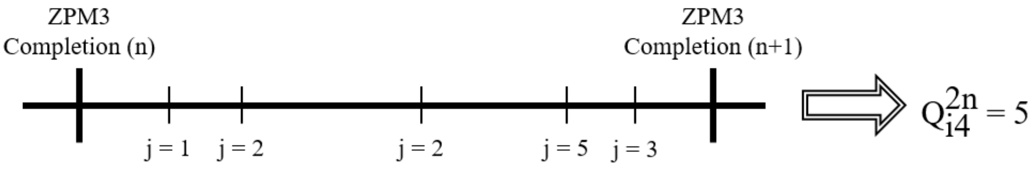


Figure 15: Visual Illustration, 2nd Quality Sub-Metric

The following table illustrates the range, target, and notes summary for Q_{ij}^{1n} and Q_{ij}^{2n} at the individual work order level.

Table 7: Quality Metric Summary

Quality		
Metric	Range	Target
Q_{ij}^{1n}	[0,1]	$1^{1,2}$
Q_{i4}^{2n}	$\{0, 1, \dots\}$	0

NOTES:

[1] One difficulty in calculating Q_{ij}^{1n} is in choosing an appropriate value of the target Threshold, Th. Inherent in this choice is a degree of subjectivity. If Th is too small, the i^{th} technician's Q_{ij}^{1n} will be much higher as the threshold will be much easier to satisfy. Likewise, if Th is too large, the i^{th} technician's Q_{ij}^{1n} will be much lower as the threshold will be much more difficult to satisfy.

To combat both these issues, it was decided to apply the logic of Case 1, 2, 3, and 4 to a range of Th, specifically the following:

$$Th = [0 \;\; 30 \;\; 60 \;\; 90 \;\; 120 \;\; 150 \;\; 180] \text{ days}$$

where 180 days was chosen as the maximum Th because that is the typical interval between ZPM3 (preventative maintenance). Q_{ij}^{1n} was then calculated for the range of thresholds, i.e. $Q_{ij}^{1n}(Th_1)$, $Q_{ij}^{1n}(Th_2)$, $Q_{ij}^{1n}(Th_3)$, $Q_{ij}^{1n}(Th_4)$, $Q_{ij}^{1n}(Th_5)$, $Q_{ij}^{1n}(Th_6)$, and $Q_{ij}^{1n}(Th_7)$ at the individual work order level.

When aggregating at the technician level, the i^{th} technician's Quality Profile (QP_{ij}) for the n^{th} work order in the work order group can be determined, i.e. how the quality of their work changes with time. The individual elements of the QP_{ij} can be aggregated over all work orders of the j^{th} type and the area under the curve can be calculated for the technician's average Q_{ij}^{1n}.

[2] In defining a threshold, Th, for Q_{ij}^{1n} it is important to note the difference between the quality threshold and the idea of a mechanical fatigue threshold. Establishment of a quality threshold is meant as an evaluation of a technician's work order completion. Mechanical design limits or fatigue thresholds, however, are different and are related to initial and remaining life of components/ systems. This research uses the idea that a technician's completed work imparts additional life to the component and/ or system if it is being properly fixed and new life if it is being properly replaced. It is noted that the resulting component life after completion of work will be different depending on if the component and/ or system is repaired vs replaced. This nuance is not captured in this initial stage of research and should be considered a target area for refinement, perhaps in conjunction with some condition-based maintenance models.

B.4 Timeliness (k = 2, T) by Individual Work Order

To evaluate the timeliness associated with a work order (k = 2), four (4) distinct sub-metrics of form T_{ij}^{mn} must be calculated for each work order. The calculation of sub-metrics T_{ij}^{1n}, T_{ij}^{2n}, T_{ij}^{3n}, and T_{ij}^{4n} is not specific to any order type.

T_{ij}^{1n}

T_{ij}^{1n} is defined as the 1st timeliness sub-metric (m = 1) for the nth work order in the jth order type for the ith technician, for i = 1, 2, …, I, j = 1, 2, 3, 4, 5, and n = 1, 2, …, N_{ij}. Specifically, T_{ij}^{1n} is the number of hours worked over all operations in the nth work order in the work order group as illustrated below:

Table 8: Tabular Illustration, 1st Timeliness Sub-Metric

Operation Line Item Number	Operation Description	Actual Hours Worked
10	Safety/ Preparation/ Documentation	2
20	Travel	1
30	Troubleshooting/ Inspection/ Service	5
40	Repair	15
50	Replace	5

$$T_{ij}^{1n} = 28\text{hrs}$$

T_{ij}^{2n}

T_{ij}^{2n} is defined as the 2nd timeliness sub-metric (m = 2) for the nth work order in the jth order type for the ith technician, for i = 1, 2, …, I, j = 1, 2, 3, 4, 5, and n = 1, 2, …, N_{ij}.

Specifically, T_{ij}^{2n} is the number of hours difference between completion of the nth work order in the work order group and its respective required deadline, as illustrated below:

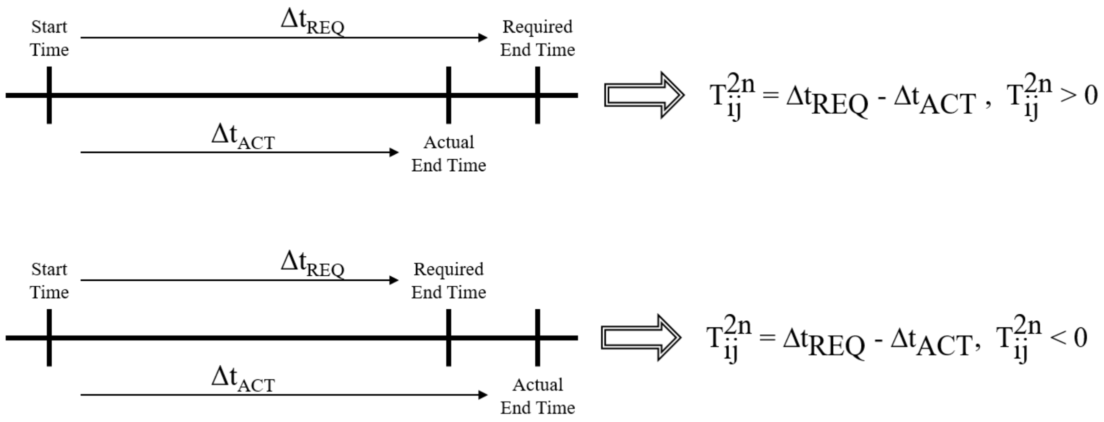


Figure 16: Visual Illustration, 2nd Timeliness Sub-Metric

T_{ij}^{3n}

T_{ij}^{3n} is defined as the 3rd timeliness sub-metric (m = 3) for the nth work order in the jth order type for the ith technician, for i = 1, 2, …, I, j = 1, 2, 3, 4, 5, and n = 1, 2, …, N_{ij}. Specifically, T_{ij}^{3n} is the number of hours the nth work order in the work order group was active, i.e. Δt from work order start to work order completion as documented in the work order management system (typically SAP or a similar system), as illustrated below:

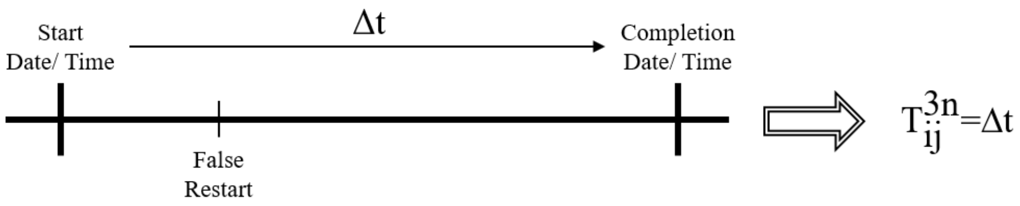


Figure 17: Visual Illustration, 3rd Timeliness Sub-Metric

T_{ij}^{4n}

T_{ij}^{4n} is defined as the 4th timeliness sub-metric (m = 4) for the nth work order in the jth order type for the ith technician, for i = 1, 2, …, I, j = 1, 2, 3, 4, 5, and n = 1, 2, …, N_{ij}. Specifically, T_{ij}^{4n} is the deviation of the number of actual hours worked in the nth work order of the work order group to the number of hours the work order was active, Δt from work order start to work order completion as documented in the work order management system (typically SAP or a similar system). Colloquially, T_{ij}^{4n} is a function of T_{ij}^{1n} and T_{ij}^{3n}, as illustrated below:

$$T_{ij}^{4n} = \mathrm{ABS}\left(T_{ij}^{1n} - T_{ij}^{3n}\right)$$

The following table illustrates the range, target, and notes summary for T_{ij}^{1n}, T_{ij}^{2n}, T_{ij}^{3n}, and T_{ij}^{4n} at the individual work order level.

Table 9: Timeliness Metric Summary

Timeliness		
Metric	Range	Target
T_{ij}^{1n}	$[0, \infty]$	Minimize[1]
T_{ij}^{2n}	$[-\infty, \infty]$[2,3]	Maximize
T_{ij}^{3n}	$[0, \infty]$	Minimize[1]
T_{ij}^{4n}	$[0, \infty]$	0[4]

<u>NOTES:</u>

[1] While the stated target for T_{ij}^{1n} and T_{ij}^{3n} is to be minimized, it is unrealistic to assume that this value will ever reach 0 as any work order that is completed should also include an amount of work completed, excluding errors in documentation. In most cases, the realistic target for T_{ij}^{3n} is to be better than the normalized average over all technicians.

[2] $+\infty$ is limited to the elapsed Δt between the official work order start date/ time and the required end date/ time

[3] In a few cases, the designated required end date was deemed illogical, e.g. a blanket input of 20 years out from start of work. In these cases, a logical proxy for the required end date was found and used.

[4] T_{ij}^{4n} targeting a value of zero places an emphasis on importance in data quality. In this regard, the actual hours worked should be as close as possible to the hours the work order has been active. A high deviation potentially indicates that some amount of work was completed and not recorded, hence leaving the work order open longer. Conversely, if the deviation is relatively small, this indicates that the actual hours worked is a close representation to the totality of work completed on a work order.

B.5 Efficiency (k = 3, E) by Individual Work Order

To evaluate the efficiency associated with a work order (k = 3), seven (7) distinct sub-metrics of form E_{ij}^{mn} must be calculated for each work order. The calculation of sub-metrics E_{ij}^{1n}, E_{ij}^{2n}, E_{ij}^{3n}, E_{ij}^{4n} , E_{ij}^{5n}, E_{ij}^{6n}, and E_{ij}^{7n} is not specific to any order type.

E_{ij}^{1n}

E_{ij}^{1n} is defined as the 1st efficiency sub-metric (m = 1) for the nth work order in the jth order type for the ith technician, for i = 1, 2, …, I, j = 1, 2, 3, 4, 5, and n = 1, 2, …, N_{ij}. Specifically, E_{ij}^{1n} is the number of actual hours worked recorded relating to Safety, Preparedness, and Documentation (SPD) in the nth work order of the work order group. Operation line item descriptions were text searched (case insensitive) against the following terms: “SPD”, “safety”, “prep”, “docum”, and “assist”. An illustration is shown below:

Table 10: Tabular Illustration, 1st, 2nd, 3rd, 4th, 5th, 6th, and 7th Efficiency Sub-Metrics

Operation Line Item Number	Operation	Actual Hours Worked	Expected Hours Worked
10	SPD	2	2
20	T	1	0.5
30	TIS	5	2
40	R1	15	12
50	R2	5	8

$$E_{ij}^{1n} = 2\text{hrs}$$

E_{ij}^{2n}

E_{ij}^{2n} is defined as the 2nd efficiency sub-metric ($m = 2$) for the nth work order in the jth order type for the ith technician, for $i = 1, 2, \ldots, I$, $j = 1, 2, 3, 4, 5$, and $n = 1, 2, \ldots, N_{ij}$. Specifically, E_{ij}^{2n} is the number of actual hours worked recorded relating to Travel (T) to and from the turbine in the nth work order of the work order group. Operation line item descriptions were text searched (case insensitive) against the following terms: "T" and "travel". An illustration is shown in Table 10 and below:

$$E_{ij}^{2n} = 1\text{hrs}$$

E_{ij}^{3n}

E_{ij}^{3n} is defined as the 3rd efficiency sub-metric ($m = 3$) for the nth work order in the jth order type for the ith technician, for $i = 1, 2, \ldots, I$, $j = 1, 2, 3, 4, 5$, and $n = 1, 2, \ldots, N_{ij}$. Specifically, E_{ij}^{3n} is the number of actual hours worked recorded relating to Troubleshooting, Inspections, and Services (TIS) in the nth work order of the work order group. Operation line item descriptions were text searched (case insensitive) against the following terms: "trouble", "inspect", "invest", "maint", "service", and "checklist". An illustration is shown in Table 10 and below:

$$E_{ij}^{3n} = 5\text{hrs}$$

E_{ij}^{4n}

E_{ij}^{4n} is defined as the 4th efficiency sub-metric (m = 4) for the nth work order in the jth order type for the ith technician, for i = 1, 2, …, I, j = 1, 2, 3, 4, 5, and n = 1, 2, …, N_{ij}. Specifically, E_{ij}^{4n} is the number of actual hours worked recorded relating to Repair (R1) in the nth work order of the work order group. Operation line item descriptions were text searched (case insensitive) against the following terms: “repair”. An illustration is shown in Table 10 and below:

$$E_{ij}^{4n} = 15\text{hrs}$$

E_{ij}^{5n}

E_{ij}^{5n} is defined as the 5th efficiency sub-metric (m = 5) for the nth work order in the jth order type for the ith technician, for i = 1, 2, …, I, j = 1, 2, 3, 4, 5, and n = 1, 2, …, N_{ij}. Specifically, E_{ij}^{5n} is the number of actual hours worked recorded relating to Replace (R2) in the nth work order of the work order group. Operation line item descriptions were text searched (case insensitive) against the following terms: “replace”. An illustration is shown in Table 10 and below:

$$E_{ij}^{5n} = 5\text{hrs}$$

E_{ij}^{6n}

E_{ij}^{6n} ≡ the 6th efficiency sub-metric (m = 6) for the nth work order in the jth order type for the ith technician, for i = 1, 2, …, I, j = 1, 2, 3, 4, 5, and n = 1, 2, …, N_{ij}. Specifically, E_{ij}^{6n} is the ratio of hours worked in SPD and T to the hours worked in TIS, R1, and R2 in the nth work order of the work order group, as illustrated in Table 10 and below:

$$E_{ij}^{6n} = \left\{\frac{E_{ij}^{1n} + E_{ij}^{2n}}{E_{ij}^{3n} + E_{ij}^{4n} + E_{ij}^{5n}}\right\} = \left\{\frac{2 + 1}{5 + 15 + 5}\right\} = 0.15$$

E_{ij}^{7n}

E_{ij}^{7n} is defined as the 7th efficiency sub-metric (m = 7) for the nth work order in the jth order type for the ith technician, for i = 1, 2, …, I, j = 1, 2, 3, 4, 5, and n = 1, 2, …, N_{ij}. Specifically, E_{ij}^{7n} is the ratio of actual hours worked to the expected number of hours worked in the nth work order of the work order group, as illustrated in Table 10 and below:

$$\text{Expected Hours Worked} = (2 + 0.5 + 2 + 12 + 8) = 24.5\text{hrs}$$

$$E_{ij}^{7n} = \left\{\frac{\text{Actual Hours Worked}}{\text{Expected Hours Worked}}\right\} = \left\{\frac{23\text{hrs}}{24.5\text{hrs}}\right\} = 0.939$$

The following table illustrates the range, target, and notes summary for E_{ij}^{1n}, E_{ij}^{2n}, E_{ij}^{3n}, E_{ij}^{4n}, E_{ij}^{5n}, E_{ij}^{6n}, and E_{ij}^{7n} at the individual work order level.

Table 11: Efficiency Metric Summary

Efficiency		
Metric	Range	Target
E_{ij}^{1n}	[0, ∞]	Minimize[1,4,7]
E_{ij}^{2n}	[0, ∞]	Minimize[2,4,7]
E_{ij}^{3n}	[0, ∞]	Maximize[3,4,7,9]
E_{ij}^{4n}	[0, ∞]	Maximize[3,4,7,9]
E_{ij}^{5n}	[0, ∞]	Maximize[3,4,7,9]
E_{ij}^{6n}	[0, ∞]	Minimize[5,7]
E_{ij}^{7n}	[0, ∞]	Minimize[6,7,8]

<u>NOTES:</u>

[1] While the stated target of E_{ij}^{1n} is to be minimized, the standards of safety, preparedness, and documentation shall not be sacrificed.

[2] While the stated target of E_{ij}^{1n} is to be minimized, the standards of safety in travel shall not be sacrificed.

[3] While the stated target of E_{ij}^{3n}, E_{ij}^{4n}, and E_{ij}^{5n} is to be minimized, no quality should be sacrificed to achieve this aim.

[4] E_{ij}^{1n}, E_{ij}^{2n}, E_{ij}^{3n}, E_{ij}^{4n}, and E_{ij}^{5n} represent the relative use of time in the n^{th} work order for specific operation types. It is beneficial to account for these outside of E_{ij}^{6n} as it allows specific operational efficiency comparisons between technicians.

[5] While it is apparent that E_{ij}^{6n} is a function of E_{ij}^{1n}, E_{ij}^{2n}, E_{ij}^{3n}, E_{ij}^{4n}, and E_{ij}^{5n}, it serves a different fundamental purpose. E_{ij}^{6n} is concerned with the comparison of indirect to direct work. While SPD and T are important, they are not directly addressing the turbine fault, as are TIS, R1, and R2. This indirect-to-direct ratio is important in determining how the technician's operation hours are spent in service of the fault to which they are assigned.

[6] E_{ij}^{7n} is compared to a pre-populated value for expected hours worked, dependent on work order type. Due to varying degrees of complexity, expected hours worked may not always be a completely fair comparison. E_{ij}^{7n} is a sub-metric where future refinements may be applied.

[7] Many operations in the case study used non-standard designations, so extensive text search was used to identify appropriate categories. If a category was not identified for an operation in the n^{th} work order, operation hours were distributed according to pre-selected ratios (SPD = 0.05, T = 0.05, TIS = 0.25, R1 = 0.35, R2 = 0.35). It is noted that this occurrence will trend certain calculations to this pre-selected distribution.

[8] Many work orders did not have expected hours worked. Therefore, E_{ij}^{7n} = #N/A

[9] While it could be argued that a technician should minimize the time spent on all tasks, given a specific level of quality, it was deemed that operations relating to TIS, R1, and R2 should not be rushed in any sense. By stating that the target is to be maximized, it assumes that the operation takes just long enough to ensure complete quality and that a longer time somewhat relates to higher quality. While this may not necessarily be true, for an initial case study it was feasible. In any case, the comparison of direct vs indirect hours is handled in E_{ij}^{6n} whose target is to be minimized.

B.6 Documentation (k = 4, D) by Individual Work Order

To evaluate the documentation associated with a work order (k = 4), three (3) distinct sub-metrics of form D_{ij}^{mn} must be calculated for each work order. The calculation of sub-metrics D_{ij}^{1n}, D_{ij}^{2n}, and D_{ij}^{3n} is not specific to any order type.

D_{ij}^{1n}

D_{ij}^{1n} is defined as the 1st efficiency sub-metric (m = 1) for the nth work order in the jth order type for the ith technician, for i = 1, 2, …, I, j = 1, 2, 3, 4, 5, and n = 1, 2, …, N_{ij}. Specifically, D_{ij}^{1n} is categorically concerned with missing data. It is the number of critical fields which are blank or #N/A, averaged over all operations in the nth work order of the work order group. If a field is blank or #N/A, then a 1 is recorded. If a field is NOT blank or #N/A, then a 0 is recorded. An illustration can be seen below:

Table 12: Tabular Illustration, 1st Documentation Sub-Metric

Field Designation	Op10 SPD	Op20 T	Op30 TIS	Op40 R1	Op50 R2
Critical Field Blank	5	0	2	0	8
Critical Field #N/A	4	3	1	5	0
Missing Score	0.141[1]	0.047	0.047	0.078	0.125
D_{ij}^{1n}	0.0876				

NOTES:

[1] In this application there were 64 designated critical fields. The sum of all missing critical fields for a single operation was divided by 64. Subsequently, scores for each operation were then averaged for D_{ij}^{1n}

D_{ij}^{2n}

D_{ij}^{2n} is defined as the 2nd efficiency sub-metric (m = 2) for the nth work order in the jth order type for the ith technician, for i = 1, 2, …, I, j = 1, 2, 3, 4, 5, and n = 1, 2, …, N_{ij}. Specifically, D_{ij}^{2n} is categorically concerned with logical inconsistencies. It is the average number of instances of anachronism between designated critical dates and times associated with operation line items in the nth work order of the work order group. If an anachronism is detected, a 1 is recorded. If no anachronism is detected, a 0 is recorded. Inconsistencies were evaluated over the following cases, with an illustration below:

Table 13: Logical Inconsistency Cases, 2nd Documentation Sub-Metric

Case	Date/ Time	Test	Date/ Time
1	Malfunction End Date	BEFORE	Malfunction Start Date
2	Malfunction End Time	BEFORE	Malfunction Start Time
3	Actual Finish Date	BEFORE	Actual Start Date
4	Actual Finish Time	BEFORE	Actual Start Time
5	Actual Finish Execution Date	BEFORE	Actual Start Execution Date
6	Actual Finish Execution Time	BEFORE	Actual Start Execution Time
7	Basic Finish Date	BEFORE	Basic Start Date

Table 14: Tabular Illustration, 2nd Documentation Sub-Metric

Designation	Op10	Op20	Op30	Op40	Op50
Case 1	0	0	0	0	0
Case 2	0	0	0	0	0
Case 3	1	1	1	0	0
Case 4	0	0	0	0	0
Case 5	1	0	0	1	1
Case 6	1	0	1	1	1
Case 7	1	1	1	1	1
Logical Score	0.571	0.286	0.429	0.429	0.429
D_{ij}^{2n}			0.429		

D_{ij}^{3n}

D_{ij}^{3n} is defined as the 3rd efficiency sub-metric ($m = 3$) for the nth work order in the jth order type for the ith technician, for $i = 1, 2, \ldots, I$, $j = 1, 2, 3, 4, 5$, and $n = 1, 2, \ldots, N_{ij}$. Specifically, D_{ij}^{3n} is categorically concerned with wrong input to critical fields. D_{ij}^{3n} evaluates individual operation line items in the nth work order of the work order group over the following three cases, with an illustration below:

Case 1 (Number of distinct operations)

Consistency in operational line items is extremely important for the calculation of multiple metrics, specifically for Efficiency. Therefore, it is ideal for each work order in the work order group to have five (5) distinct operations: SPD, T, TIS, R1, and R2. Case 1 is concerned with the number of distinct operations in the nth work order. If the nth work order does not have five unique operations, then it receives a score of 1 for Case 1. If the nth work order does have five unique operations, then it receives a score of 0 for Case 1.

Case 2 (Population of actual work hours)

In addition to consistency in operation line items, it is important for each operation to correctly record its associated hours, Actual Hours Worked in this instance. If the specific operation line item in the nth work order does not have any registered Actual Work Hours, it receives a 1 for Case 2. If the specific operation line item in the nth work order does have registered Actual Work Hours, it receives a 0 for Case 2.

Case 3 (Correct operation line items)

Much like Case 1, Case 3 is concerned with consistency in operation line items. However, Case 3 is specifically interested in whether each operation line item corresponds to a standard operation, i.e. SPD, T, TIS, R1, or R2. If the specific operation line item description in the n^{th} work order does not belong to any of the specified categories, it receives a 1 for Case 3. If the specific operation line item description in the n^{th} work order does belong to one of the specified categories, it receives a 0 for Case 3.

Table 15: Tabular Illustration, 3rd Documentation Sub-Metric

WO100001579		
Operation Number	Operation Description	Actual Hours Worked
10	Crew mobilization	0
20	Root cause of core and disposal	0
30	Freight for gearbox	0
40	Installation services	0
50	Crane services	0
60	Tower cleaning from oil spill	0
70	Standby charges	0

Table 16: Tabular Illustration Continued, 3rd Documentation Sub-Metric

Case	Op10	Op20	Op30	Op40	Op50	Op60	Op70	Score
Case 1	1							1
Case 2	1	1	1	1	1	1	1	1
Case 3	1	1	1	0[1]	0[1]	1	1	0.714
D_{ij}^{3n}	0.905							
NOTES: [1] Even though Op40 and 50 did not register as SPD, T, TIS, R1, or R2, the term “service” did register with the standard TIS designation by the text search used across Efficiency and Documentation metrics.								

The following table illustrates the range, target, and notes summary for D_{ij}^{1n}, D_{ij}^{2n}, and D_{ij}^{3n} at the individual work order level.

Table 17: Documentation Metric Summary

Documentation		
Metric	Range	Target
D_{ij}^{1n}	[0, 1][1]	0
D_{ij}^{2n}	[0, 1]	0[2]
D_{ij}^{3n}	[0, 1]	0[3]

NOTES:

[1] It was found that many work orders had the same critical fields which were designated blank or #N/A. It is expected, therefore, that there is some level of correlation between D_{ij}^{1n} of different work orders

[2] It was found that very few work orders suffered from a significant number of logical inconsistencies in dates and times, i.e. anachronisms

[3] Many operations used non-standard designations, so extensive text search was used to identify whether the appropriate categories were or were not satisfied. In the ideal case, operation line item description would simply be selected from a pulldown list of standard items.

B.7 Task Completion Rate (k = 5, TCR) by Technician

To evaluate the task completion rate associated with a technician (k = 5), two (2) distinct sub-metrics of form TCR_{ij}^{m} must be calculated for each technician. The calculation of sub-metrics TCR_{ij}^{1} and TCR_{ij}^{2} is not specific to any order type.

TCR_{ij}^{1}

TCR_{ij}^{1} is defined as the 1st task completion rate sub-metric (m = 1) in the jth order type for the ith technician, for i = 1, 2, …, I and j = 1, 2, 3, 4, 5. Specifically, TCR_{ij}^{1} is the number of work orders of the jth type the ith technician has completed over their entire history, as illustrated below:

Table 18: Tabular Illustration, 1st Task Completion Rate Sub-Metric

			Technician				
			AA	BB	CC	DD	EE
			i = 1	i = 2	i = 3	i = 4	i = 5
Order Type	ZPM0/6	j = 1	2	1	5	0	1
	ZPM1	j = 2	15	10	4	20	10
	ZPM2/4	j = 3	5	12	7	9	15
	ZPM3	j = 4	7	5	1	8	3
	ZPM5	j = 5	3	1	5	2	4

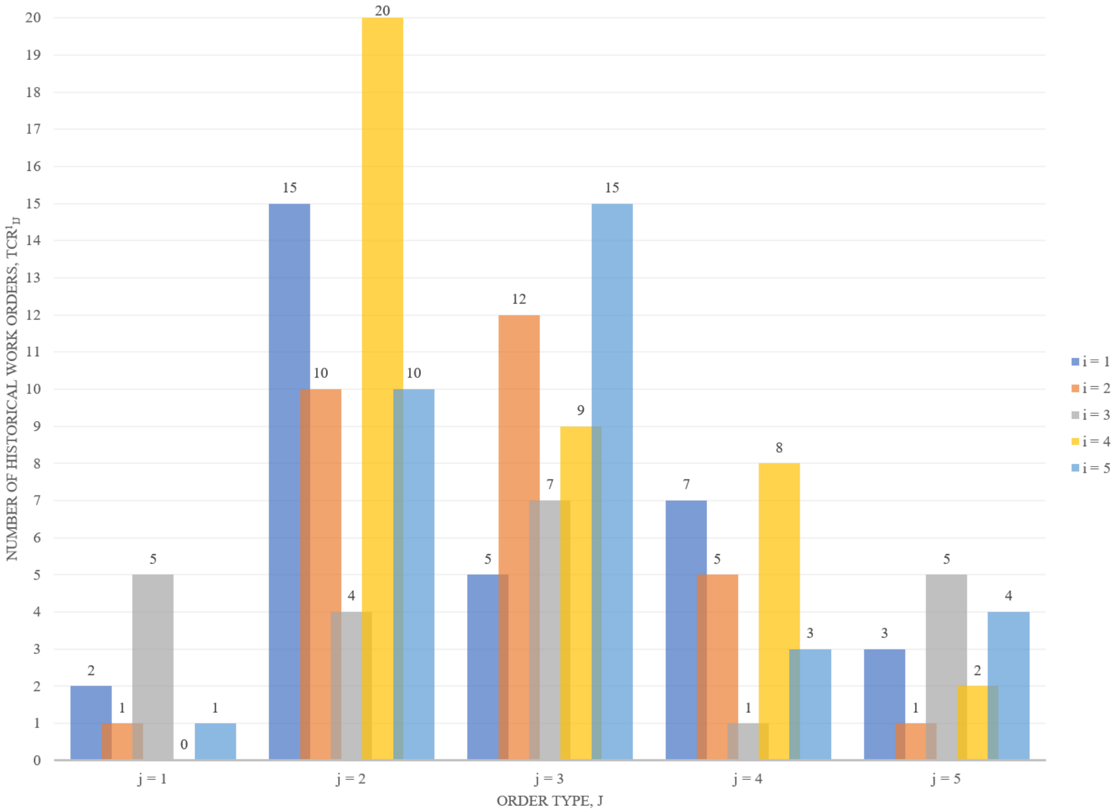


Figure 18: Visual Illustration, 1st Task Completion Rate Sub-Metric

TCR_{ij}^2

TCR_{ij}^2 is defined as the 2nd task completion rate sub-metric (m = 2) in the jth order type for the ith technician, for i = 1, 2, …, I and j = 1, 2, 3, 4, 5. Specifically, TCR_{ij}^2 is a sub-set of TCR_{ij}^1 and is the number of work orders of the jth type the ith technician has completed over the last 1 year.

$$\mathrm{TCR}_{ij}^2 = \mathrm{TCR}_{ij_{\in \text{ Last 1 Year}}}^1$$

The following table illustrates the range, target, and notes summary for $\text{TCR}_{\text{ij}}^{1}$ and $\text{TCR}_{\text{ij}}^{2}$ at the technician level.

Table 19: Task Completion Rate Metric Summary

Task Completion Rate		
Metric	Range	Target
$\text{TCR}_{\text{ij}}^{1}$	{0, 1, …}	Maximize[2]
$\text{TCR}_{\text{ij}}^{2}$	{0, 1, …}[1]	Maximize[2]

NOTES:

[1] Recent relevant experience is likely to be just as important as a technician's overall body of work as technical documentation and/ or best practices can continually evolve, amongst other changing aspects of maintenance. Additionally, the time period of 1 year is somewhat subjective based on the user and can be exchanged with a different time period if there is justification.

[2] It is noted that $\text{TCR}_{\text{ij}}^{1}$ will continuously increase, while $\text{TCR}_{\text{ij}}^{2}$ will either increase or decrease depending on a technician's assignments over the past year. This gives rise to special uses of each sub-metric. For instance, $\text{TCR}_{\text{ij}}^{1}$ could give a good indication of a technician who may have a large history of in-depth troubleshooting experience over a large variety of turbine components and models. On the other hand, $\text{TCR}_{\text{ij}}^{2}$ could give a good indication of a technician who could potentially offer insight on an issue dealing with a recently developed component addition to a turbine.

B.8 Task-Based Certification (k = 6, TBC) by Technician

TBC is special in that it does not require information from a specific work order or group of work orders. TBC is calculated strictly based on the technician's certification and training history and is proposed for two distinct uses: 1) relative comparison of basic technician aptitudes, marked by completion of certification and/ or training tasks, and 2) strict satisfaction of certification and/ or training requirements for specific work order types.

To evaluate the task-based certification associated to a technician (k = 6), three (3) distinct sub-metrics of form TBC_{ij}^{m} must be calculated for each technician. By mapping specific certification and training tasks to their related work order types, potentially with weighting applied to certain tasks, task-based certification sub-metrics can be calculated for specific order types. The calculation of sub-metrics TBC_{ij}^{1}, TBC_{ij}^{2}, and TBC_{ij}^{3} is not specific to any order type.

It is important to note that, currently, the data infrastructure used to formulate Quality, Timeliness, Efficiency, Documentation, and Task Completion Rate metrics, provided by a large wind farm owner and operator, does not yet allow structuring and calculation of TBC. Therefore, the following derivations are strictly a proposed framework which is subject to change as more structure is defined.

B.8.1 TBC Task Mapping

It is necessary to create a relation between the sets of certification and training tasks to the work order types which they enable the technician to properly complete.

Although the subject of the case study does not have the appropriate structure in place to support TBC calculation, their training and certification system will be used for high level illustration of how a task mapping may be applied.

Task mapping, at its highest level, relates completion of a certification or training tasks towards credit in the appropriate TBC metric for the specific work order types to which they apply. As an example, the following certification task mapping with three (3) certification levels is illustrated below. A task is mapped with a 1 if it is related to or a 0 if it is not related to the appropriate work order type, respectively:

Table 20: Tabular Illustration, Task-Based Certification Mapping

Cert Level	Cert/ Task	ZPM0/6	ZPM1	ZPM2/4	ZPM3	ZPM5
1	1	1	1	1	1	1
	2	1	1	1	1	1
	3	1	0	0	1	0
	4	1	0	0	1	0
2	1	0	1	0	1	0
	2	1	1	1	1	0
	3	0	0	1	1	1
3	1	1	0	1	0	1
	2	1	0	0	0	1
	3	0	1	0	0	1
	4	0	1	1	0	1
	5	1	1	1	1	0

Therefore, when calculating TBC_{ij}^{1}, TBC_{ij}^{2}, and/ or TBC_{ij}^{3} with respect to specific order types (j = 1, 2, 3, 4, or 5), only those tasks which have been mapped with a 1 to that order type will be considered. Additionally, depending on the necessity or relative importance of a certain task, non-similar weights may be utilized to make a specific task worth more to the overall calculation of TBC_{ij}^{1}, TBC_{ij}^{2}, and/ or TBC_{ij}^{3}.

An added benefit of using a holistic task mapping system is the ability to use drill down mechanisms when analyzing a specific TBC_{ij}^{m}. For instance, if the i^{th} technician was up for consideration for a ZPM0/6 work order (j = 1), a director may need to check the technician's basic certifications for access to working with the appropriate equipment. They would isolate the appropriate TBC_{ij}^{m} and drill down within that metric structure to determine which of the individual tasks mapped with a 1 have been completed by the technician. If they have completed the requisite tasks, they may be assigned.

Task mapping forms the very basic structure for calculation of TBC_{ij}^{1}, TBC_{ij}^{2}, and TBC_{ij}^{3}. However, additional structure must be put in place to allow automatic and timely updating of the database or documentation detailing those training and/ or certification tasks which the technicians have completed. The mapping is only fully useful when applied to the technician's history of completed certification and/ or training tasks.

What follows is the detailed calculation of the proposed TBC_{ij}^{1}, TBC_{ij}^{2}, and TBC_{ij}^{3} with reference to Table 20 for illustration. As stated earlier, these calculations are derived with respect to the inherent structure of training and certification tasks at a large wind farm owner and operator and can differ depending on application.

TBC_{ij}^{1}

TBC^1_{ij} is defined as the 1st task-based certification sub-metric (m = 1) in the jth order type for the ith technician, for i = 1, 2, …, I and j = 1, 2, 3, 4, 5. Specifically, TBC^1_{ij} is the completion percentage of the 1st level of technician certification tasks, as illustrated in Table 20 and below:

Table 21: Tabular Illustration, 1st Task-Based Certification Sub-Metric

Cert Level	Cert/ Task	Tech. Status (1 = Complete, 0 = Incomplete)
1	1	1
	2	1
	3	1
	4	0

Therefore, by multiplying the Technician Status with its respective mapping in Table 20, the appropriate TBC^1_{ij} for the ith technician is calculated. The calculation result is one of four cases, as shown below, aided with illustration:

<u>Case 1 (Technician status = 1, Mapping = 1)</u>

- The ith technician is credited with a completed task
- The completed task is mapped to the jth order type
- The completed task is counted toward the ith technician's completion percentage in the jth order type

<u>Case 2 (Technician status = 1, Mapping = 0)</u>

- The ith technician is credited with a completed task

- The completed task is not mapped to the j^th order type
- The completed task is not counted toward the i^th technician's completion percentage in the j^th order type

Case 3 (Technician status = 0, Mapping = 1)

- The i^th technician is credited with a non-completed task
- The non-completed task is mapped to the j^th order type
- The non-completed task is counted toward the i^th technician's completion percentage in the j^th order type

Case 4 (Technician status = 0, Mapping = 0)

- The i^th technician is credited with a non-completed task
- The non-completed task is not mapped to the j^th order type
- The non-completed task is not counted toward the i^th technician's completion percentage in the j^th order type

Table 22: Tabular Illustration Continued, 1st Task-Based Certification Sub-Metric

Cert Level	Cert/ Task	i^{th} Tech. Status	ZPM0/6 $j = 1$	ZPM1 $j = 2$	ZPM2/4 $j = 3$	ZPM3 $j = 4$	ZPM5 $j = 5$
1	1	1	1	1	1	1	1
	2	1	1	1	1	1	1
	3	1	1	0	0	1	0
	4	0	1	0	0	1	0
TBC_{ij}^{1}			0.75	1.00	1.00	0.75	1.00

TBC_{ij}^{2}

TBC_{ij}^{2} is defined as the 2nd task-based certification sub-metric (m = 2) in the jth order type for the ith technician, for i = 1, 2, …, I and j = 1, 2, 3, 4, 5. Specifically, TBC_{ij}^{2} is the completion percentage (%) of the 2nd level of technician certification tasks, as illustrated in Table 20 and below, similarly to TBC_{ij}^{1}:

Table 23: Tabular Illustration, 2nd Task-Based Certification Sub-Metric

Cert Level	Cert/ Task	ith Tech. Status	ZPM0/6 j = 1	ZPM1 j = 2	ZPM2/4 j = 3	ZPM3 j = 4	ZPM5 j = 5
2	1	0	0	1	0	1	0
	2	1	1	1	1	1	0
	3	0	0	0	1	1	1
TBC_{ij}^{2}			1.0	0.50	0.50	0.33	0.00

TBC_{ij}^{3}

TBC_{ij}^{3} is defined as the 3rd task-based certification sub-metric (m = 3) in the jth order type for the ith technician, for i = 1, 2, …, I and j = 1, 2, 3, 4, 5. Specifically, TBC_{ij}^{3} is the completion percentage (%) of the 3rd level of technician certification tasks, as illustrated in Table 20 and below, similarly to TBC_{ij}^{1}:

Table 24: Tabular Illustration, 3rd Task-Based Certification Sub-Metric

Cert Level	Cert/ Task	ith Tech. Status	ZPM0/6 j = 1	ZPM1 j = 2	ZPM2/4 j = 3	ZPM3 j = 4	ZPM5 j = 5
3	1	1	1	0	1	0	1
	2	1	1	0	0	0	1
	3	0	0	1	0	0	1
	4	1	0	1	1	0	1
	5	0	1	1	1	1	0
TBC_{ij}^{3}			0.67	0.33	0.67	0.00	0.75

The following table illustrates the range, target, and notes summary for TBC_{ij}^{1}, TBC_{ij}^{2}, and TBC_{ij}^{3} at the technician level.

Table 25: Task-Based Certification Metric Summary

Task-Based Certification		
Metric	Range	Target
TBC_{ij}^{1}	[0, 1][1,2,3]	1
TBC_{ij}^{2}	[0, 1][1,2,3]	1
TBC_{ij}^{3}	[0, 1][1,2,3]	1

NOTES:

[1] It is important to restate that the task-based certification performance metrics may only be accomplished if there is a robust internal structure to support data collection and manipulation of a technician's historical training and/ or certification. Ideally, a linked DB such as MySQL would have records of technician training and/ or certification and would be linked to whichever online service or manual service administers and proctors the training.

[2] It is up to the user to determine whether specific weights will be applied to certain tasks within a certification level. However, all weights must add to the value 1 over all tasks within the certification level to have the desired effect.

[3] TBC_{ij}^{1}, TBC_{ij}^{2}, and TBC_{ij}^{3} all may be used in the eventual formulation of the IP assigning technicians to tasks based on their performance metrics. In fact, the task-based certification metrics may be best suited to form "hard" constraints which require definite certification levels to be considered for assignment to certain tasks.

APPENDIX C

CASE STUDY

C.1 Case Study & Use Case Methodology

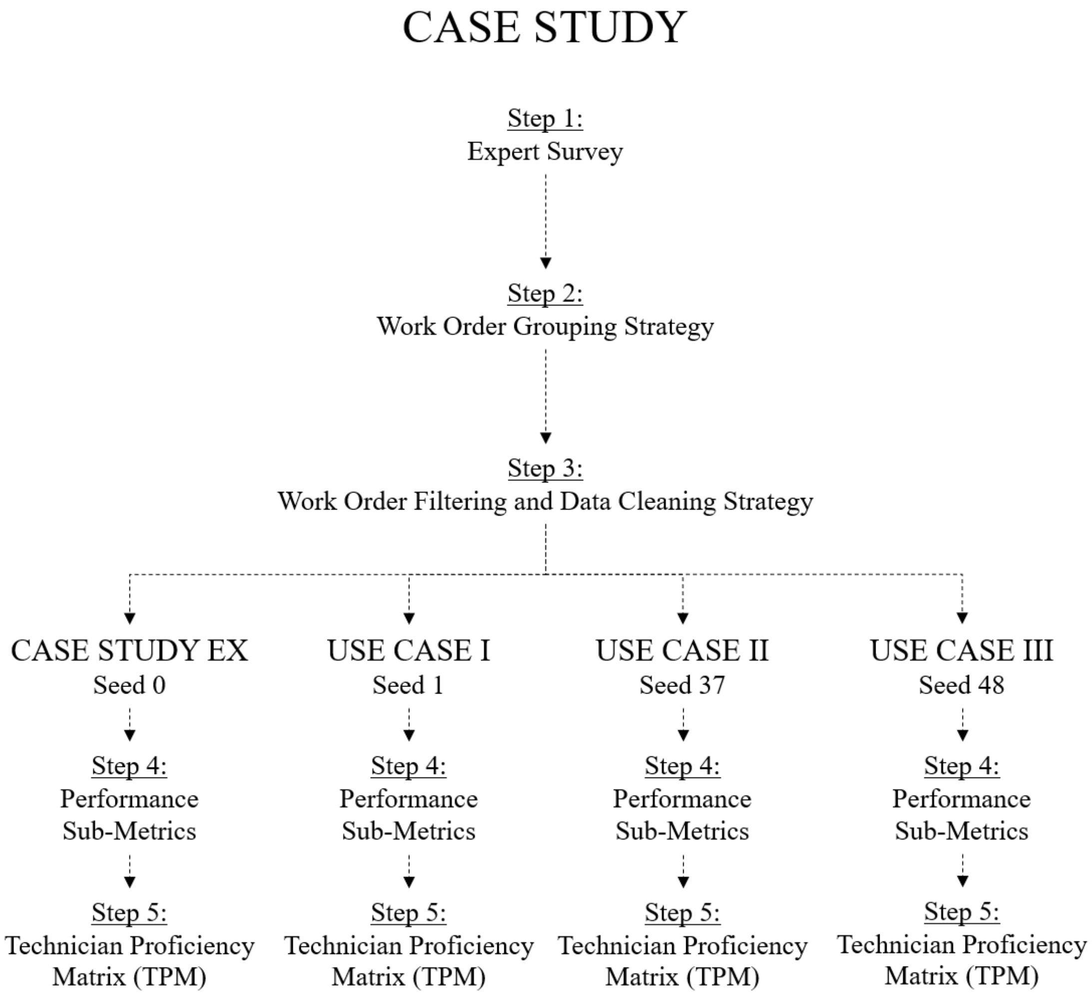


Figure 19: Case Study & Use Case Methodology

C.2 Case Study Notes

C.2.1 Note 1: Technician Recording

The large wind farm owner and operator does not currently record the individual technicians assigned to each work order. While this functionality is currently being addressed, it was not available at the time of data evaluation. To simulate this data, 10 technicians were created and randomly assigned in teams of 3 to each work order according to a uniform distribution, without replacement. While the assignment of technicians to work orders was not representative of reality, the completed work orders and respective sub-metrics to which the analytically generated technicians were assigned was representative of reality. Therefore, the conclusions drawn at the end of the case study on the generated metrics are valid if the wind farm had randomly assigned their 10 technicians to all work orders. Obviously, this would not have realistically been the case, but is a plausible situation for results demonstration.

C.2.2 Note 2: Operation Description Consistency

The large wind farm owner and operator does not currently have in place standard operation line item descriptions. The proposal for individual operation line item descriptors in Appendix B.5 is to be one of SPD, T, TIS, R1, and R2. If the operation line item descriptor in the actual work order is significantly different than these pre-defined terms, it becomes extremely difficult to categorize the operation. If the operation cannot be categorized into one of the previously defined descriptors, either by direct matching or through relevant text search, then the operation’s hours worked were accumulated and distributed to pre-defined operations based on a user selected distribution. The current distribution is as follows: SPD = 0.05, T = 0.05, TIS = 0.20, R1 = 0.35, and R2 = 0.35. While it is recognized that this is not ideal and will trend the Efficiency sub-metrics toward this distribution and its respective E_{ij}^{6n} ratio, the scenario is plausible for results demonstration.

C.2.3 Note 3: Applicable Dates

The large wind farm owner and operator designated the date range of post – January 1, 2017 as the case study range. This date range was selected as they had made a significant shift in policy to place greater emphasis on data quality at this time. While the holistic generation of the Technician Proficiency Matrix has been proven to execute over the entire history of all of their wind farms and wind sub-farms, the case study was restricted to only those work orders which started or finished from January 1, 2017 to March 15, 2018, the date on which the case study was completed.

C.3 Performance Sub-Metrics (Aggregated & Normalized)

OrderType	TECH	Q1	Q2	T1	T2	T3	T4	E1	E2	E3	E4	E5	E6	E7	D1	D2	D3	TCR1	TCR2
ZPM1	1	-0.609		0.761	-1.197	0.457	0.476	0.822	0.819	0.640	-1.161	0.424	0.308	1.315	0.168	1.744	0.393	-0.850	-0.108
ZPM2/4	1	0.414		-0.903	0.351	-1.111	-1.094	-0.422	-0.422	1.195	-0.124	-0.124	0.018	-1.431	-1.080	-0.111	0.149	0.594	0.457
ZPM3	1	0.401	0.369	0.745	-0.548	0.879	0.819	0.485	0.083	-0.739	-0.989	-0.782	-0.158	0.760	-0.643	1.479	0.314	1.193	1.144
ZPM1	2	0.588		-1.585	1.000	0.252	0.284	-0.993	-0.947	-0.311	1.538	0.957	-0.041	-0.261	-1.062	0.033	-0.183	0.750	0.614
ZPM2/4	2	-1.808		1.579	-0.442	0.693	0.652	0.971	0.971	-1.107	-1.617	-1.617	0.065	0.235	-0.855	-0.320	0.628	0.594	0.965
ZPM3	2	1.081	0.850	0.566	2.463	0.794	0.785	-0.685	-1.212	-0.601	-0.505	0.612	-0.977	0.539	-1.125	-0.034	0.445	0.659	0.858
ZPM0/6	3																		
ZPM1	3	0.261		0.331	1.277	0.737	0.721	0.882	0.647	0.064	-0.534	1.002	1.925	-1.501	1.434	-0.155	0.002	-0.850	-1.101
ZPM2/4	3	-0.996		-1.200	-1.851	0.559	0.555	-1.398	-1.398	1.117	0.445	0.445	-1.740	-0.078	-0.381	1.981	0.043	-0.891	0.457
ZPM3	3	-0.295	-0.901	0.612	-1.044	-0.733	-1.370	-0.286	0.143	-0.626	1.001	-0.076	0.148	0.541	1.025	-0.382	-0.075	-0.231	-0.572
ZPM0/6	4																		
ZPM1	4	0.493		-1.458	0.168	0.698	0.682	-1.435	-1.756	1.792	0.264	0.365	-0.293	-1.025	1.138	-1.475	-0.594	1.949	0.704
ZPM2/4	4	0.092		-0.685	0.561	-1.225	-1.205	-0.392	-0.392	0.695	0.292	0.292	-0.170	-0.078	0.371	-0.272	-0.586	0.297	-0.559
ZPM3	4	-1.533	0.038	0.537	-0.017	-0.056	-0.396	0.213	0.844	-0.550	1.245	1.384	0.420	0.563	0.781	0.245	-1.228	1.548	1.144
ZPM0/6	5																		
ZPM1	5	-1.177		0.479	0.430	0.914	0.902	0.452	0.112	1.125	-0.525	-1.016	-0.259	0.422	-1.815	1.331	-0.046	0.350	1.065
ZPM2/4	5	-0.826		0.700	0.369	0.618	0.656	-0.039	-0.039	-1.346	0.777	0.777	-1.401	0.627	1.541	-0.948	-1.444	-1.782	-1.066
ZPM3	5	0.351	1.444	0.631	-0.509	1.505	1.723	-0.610	-0.660	-0.647	-1.044	-0.473	-0.901	0.580	-0.797	0.996	1.983	-1.121	-0.572
ZPM1	6	-0.383		1.485	-0.298	-1.635	-1.643	0.388	0.679	-0.630	-1.253	-1.037	0.624	0.107	0.852	-0.621	0.695	-1.350	-1.642
ZPM2/4	6	1.269		1.334	1.951	-1.915	-1.942	1.362	1.362	-0.909	-1.214	-1.214	1.033		1.599	-1.273	-1.444	-0.891	-1.574
ZPM3	6	-0.741	0.251	0.561	-0.635	0.891	0.890	1.870	1.364	-0.518	-1.532	-0.863	1.925	0.569	-0.217	-1.158	0.862	-1.655	-1.716
ZPM1	7	-0.976		0.171	0.705	0.842	0.795	0.446	0.175	-0.240	-0.279	0.637	0.966	0.430	-0.505	-0.427	-0.311	-0.550	0.162
ZPM2/4	7	0.146		-0.639	0.032	0.579	0.570	-0.460	-0.460	0.321	0.876	0.876	0.208	0.431	-0.521	1.004	0.787	0.891	0.457
ZPM3	7	0.020	-1.832	-1.301	0.799	-0.976	-0.595	-0.646	-0.902	1.309	-0.007	-0.702	-0.273	-1.207	-0.691	-0.164	-0.033	0.303	-0.572
ZPM1	8	2.251		-0.287	0.075	0.330	0.394	0.150	0.835	-1.380	1.372	0.106	-1.443	0.026	-0.233	-1.053	-1.588	-0.450	-1.281
ZPM2/4	8	0.739		-0.875	-0.870	0.588	0.553	-1.310	-1.310	0.382	1.060	1.060	-0.268	-0.078	0.462	0.258	1.443	1.485	1.473
ZPM3	8	1.783	-1.023	0.665	-0.339	0.152	-0.103	1.283	1.191	-0.641	0.038	-0.588	1.297	0.750	-0.217	-1.655	-0.033	0.303	-0.286
ZPM1	9	-0.624		-0.697	-2.028	-1.325	-1.344	-1.711	-1.416	0.209	-0.403	0.547	-1.038	-1.062	-0.272	0.551	2.234	0.150	0.523
ZPM2/4	9	1.269		0.121	0.292	0.559	0.648	1.375	1.375	0.739	-1.247	-1.247	1.481	-1.431	-1.185	-0.948	1.010	-0.594	-1.066
ZPM3	9	0.104	0.877	-1.692	0.153	-1.177	-0.787	-1.489	-1.400	1.664	0.607	2.005	-1.216	-1.716	-0.217	1.136	-1.034	-0.587	1.144
ZPM1	10	0.176		0.801	-0.132	-1.271	-1.266	0.998	0.851	-1.269	0.981	-1.985	-0.749	1.548	0.296	0.071	-0.603	0.850	1.065
ZPM2/4	10	-0.299		0.568	-0.393	0.655	0.607	0.313	0.313	-1.088	0.751	0.751	0.774	1.803	0.049	0.629	-0.586	0.297	0.457
ZPM3	10	-1.171	-0.075	-1.324	-0.325	-1.280	-0.967	-0.134	0.548	1.349	1.186	-0.517	-0.265	-1.378	2.100	-0.462	-1.202	-0.409	-0.572

Figure 20: Performance Sub-Metrics (Aggregated & Normalized)

C.4 Technician Performance Metrics

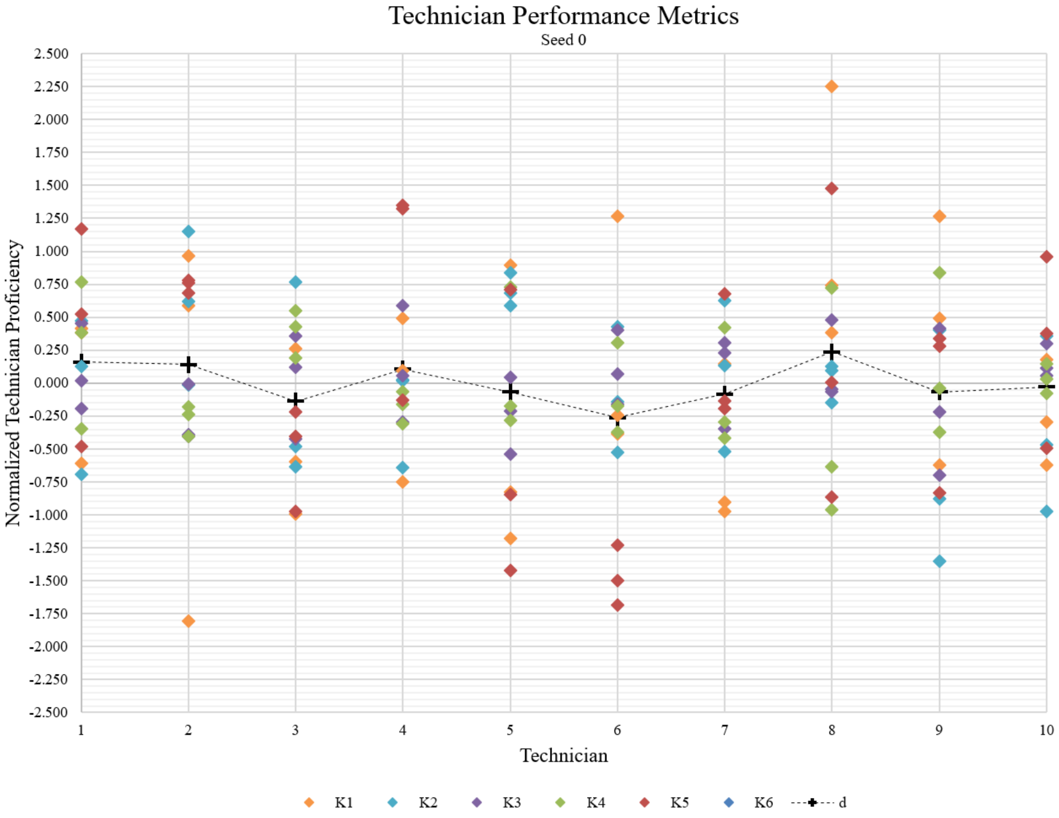


Figure 21: Technician Performance Metrics

C.5 Technician Work Order Proficiency

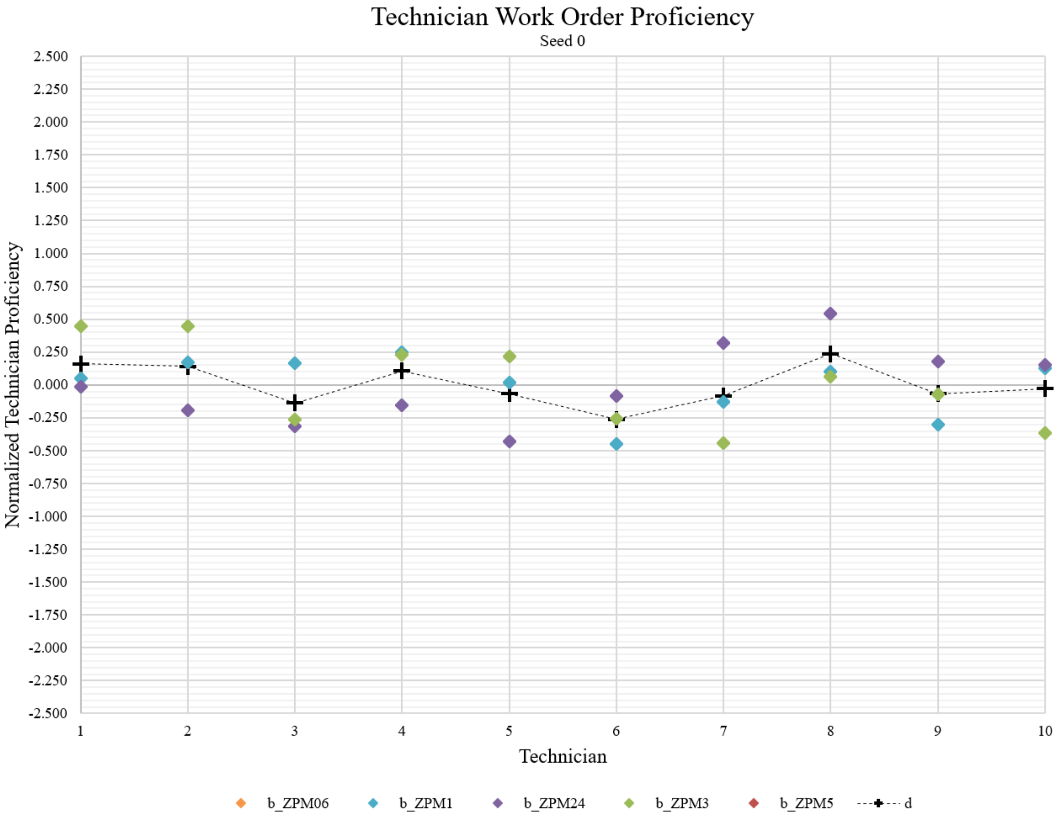


Figure 22: Technician Work Order Proficiency

C.6 Technician Attribute Proficiency

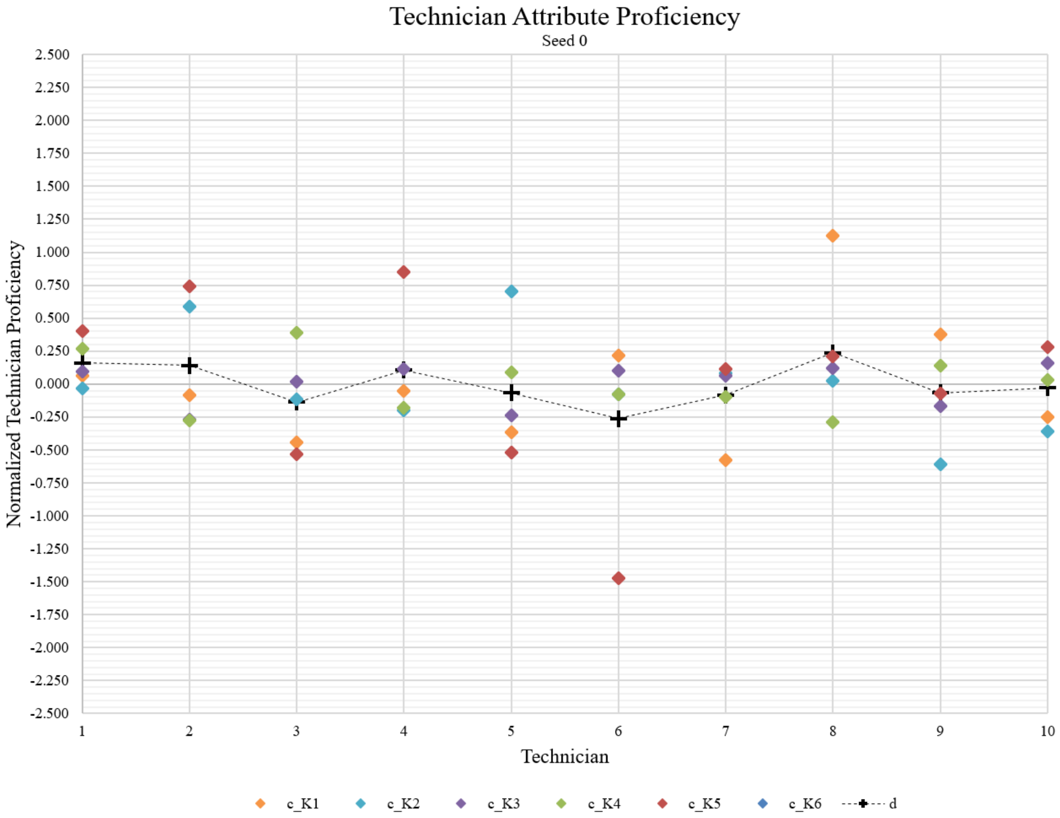


Figure 23: Technician Attribute Proficiency

APPENDIX D

DISCUSSION

D.1 Excellence in Data Quality

To generate performance metrics for use in informing decisions without attempt at enabling excellence in data quality is counterintuitive. In general, poor quality input begets poor quality output. Heinrich, et al. 2018 effectively conveyed the importance of data quality with their opening statement:

> "Due to rapid technological development, companies increasingly rely on data to support decision making and to gain a competitive advantage. To make informed and effective decisions, it is crucial to assess and ensure the quality of the underlying data."[62]

Following this opening declaration, there are many cited figures which illustrate the uncertainty in executive management decisions that poor data quality inspires. In addition to eliciting ill-conceived decisions and general distrust in data, poor data quality can also have disastrous measurable effects on business outcomes. According to a 2017 Gartner article on establishing a business case for data quality improvement, "poor data quality destroys business value. Recent Gartner research indicates that the average financial impact of poor data quality on organizations is $9.7 million per year."[89] With such a prevalent effect on high profile business decisions, it is important to ensure that any metrics which influence decisions are based on high quality data.

In derivation and evaluation of the technician performance metrics for a large wind farm owner and operator, four (4) critical elements were identified which must be addressed for quality, informed decisions to be made. While inaction on any of these items does not invalidate resulting performance metrics, it allows a specter of uncertainty to pervade potential decisions. The following four critical elements must eventually be addressed to fully actualize the potential of the holistic generation of technician performance metrics:

1. Consistent and accurate data entry
2. Database consistency
3. Technician recording
4. Operation description consistency

While not an exhaustive list, if addressed, these four key data quality issues will eliminate many of the complications and complexities of performance metric calculation. What follows is a critical discussion and recommendation on each of these key data quality issues.

D.1.1 Consistent and Accurate Data Entry

Among the 3 databases, 111 data fields, and 1 to sometimes 5 or greater number of operations per work order or notification specific to this case study, it is easy to see how individual pieces of information may be incorrectly input. Yet, individual pieces of inconsistent or incorrect information can aggregate to an almost incoherent set of operations, a notification, or a work order. A simple illustration of this phenomena is when a technician records all information in each operation for a work order, except the “actual hours worked” field, which they leave blank (resulting in 0s and #N/As). This simple exclusion of one data field from 61 designated critical fields completely renders the efficiency performance sub-metric useless and compromises the integrity of the documentation performance sub-metric. Additionally, after aggregation and calculations, the performance metrics and proficiencies are now of suspect quality. To combat this very prevalent issue, a set of precautions in the relational work order system and/ or database structure is the simplest form of response.

Perhaps the greatest source of input inconsistency and inaccuracy observed in the case study of a large wind farm owner and operator stems from the use of free-form input fields. A free-form input field is one that accepts any user input, i.e. characters, numbers, dates, times, etc. Free-form input is extremely difficult to incorporate into repeatable performance metric calculations. To combat this issue, it is proposed that each user input data field be categorized into appropriate forms of input and its respective input be restricted based on categorization. Some examples of appropriate forms of input are pre-defined input, class restrictions, and logical input checks, amongst others.

An example of a pre-defined input to consider is that of the designated critical data field, “operation line item description”, as mentioned previously in Appendix B.5. It was previously proposed that each operation be designated as one of five pre-defined operations: SPD, T, TIS, R1, or R2. In practice, when the technician or manager enters operational information into the relation work order system, often SAP or some similar software, they would only be able to choose from among pre-defined operation descriptions in a pull-down list.

Similar in restricting user input, class restrictions allow only input of specific classes, i.e. only text in designated character fields, integers in designated integer fields, etc. Class restrictions are also especially effective when used in conjunction with logical input checks. Logical input checks could be extremely useful in date and/ or time input, not allowing the user to input data that falls outside logical ranges. Additionally, they could be used as a Boolean test to register whether input has been recorded, as in the case of “actual hours worked” for the case study.

By allowing users to only input from pre-defined items, specific classes, or within logical boundaries, much confusion and complexity in downstream calculation and inference can be eliminated. It is incumbent upon the operations manager or database engineer to evaluate closely the input needed for complete performance metric calculation. Through this evaluation, they may then enact restrictions of user input freedom to avoid inconsistent and/ or inaccurate input.

D.1.2 Database Consistency

Often, the operations manager may need to use information from multiple databases. In the case study, for example, three distinct databases were queried and downloaded, one each for work orders, notifications, and operations. As separate databases may carry similar or identical data fields, often used as keys when joining, it is important to maintain the integrity of individual data fields throughout operation.

This is especially important when joining databases. Typically, when joining databases, the user defines the data fields which act as keys, i.e. data fields present in multiple databases used for matching instances. When choosing keys, the user must be diligent in determining that the data fields are indeed identical across databases and not just similar. It is important to distinguish identical data fields from those which may appear to be identical by title/ header, but actually carry distinct information. This meticulousness is important because, if not scrutinized, operations with multiple databases can actually mask and/ or distort much of the data which may be needed for performance metric calculation.

Diligence must also be given to input in similar data fields across multiple databases. It is a fairly common mistake for a user to input the exact same data in two or more data fields with similar meanings when, in fact, those data fields served distinct purposes. Because of these types of errors, potentially critical data may not be captured because the user misunderstood the intended meaning of the data field. This effect is compounded when input is required across multiple databases or data forms.

It is therefore recommended that any database or set of databases used for performance metric calculations be evaluated for identical and distinct data fields. The following cases should be easily distinguishable through examination of the title/ header of the data field or its description or key:

- Multiple data fields in a single database or in multiple databases are identical in meaning and purpose
- Multiple data fields in a single database or in multiple databases are distinct in meaning and purpose

If data fields are considered distinct, yet have identical information, this is likely an indication of confusion on the part of the user which should be remedied through data field re-branding or usage training.

D.1.3 Technician Recording

As mentioned in Note 1 of the case study of a large wind farm owner and operator, there is currently no recorded identification of technicians which complete a work order. This does not affect the physical recording of individual work order data or calculation of individual work order performance sub-metrics, but it does make it impossible to aggregate performance metrics and create proficiencies. Because of this, the effectiveness of the Personnel Deployment Strategy is greatly diminished as there is no avenue to develop the technician specific performance metrics which act as input to the proposed task-to-team assignment integer program, discussed later.

As such, it is recommended to create a new data field(s) or repurpose a non-critical data field(s) to act as input for those technicians which completed specific work orders. Ideally, the data field(s) would be specific to each work order operation or notification operation as this would allow the most flexibility in aggregation techniques. It is important to consider the recommendations in the discussion on consistent and accurate data entry regarding pre-defined data input. Ideally, when a user is inputting the one or more technicians who completed the work order, they would select the technicians from a pre-defined list of technician identifiers.

D.1.4 Operation Description Consistency

There is currently no pre-defined list of standard operation line item descriptors for individual work order or notification operations. Because of this, the user has complete free-form input for the operation line item description. This introduces considerable complexity in allocating actual hours worked for individual operations, among other related data fields.

Therefore, as mentioned in Appendix B.5, it is proposed that operation line item descriptors be selected from one of a pre-defined list: SPD, T, TIS, R1, and R2. By selecting from a pre-defined list, much potential confusion and complexity is avoided. Additionally, calculating efficiency and documentation performance sub-metrics from operations wholly contained within a pre-defined list avoids the necessity of detailed text search and pre-defined allocation distributions.

It should be mentioned that the proposed list of pre-defined operational descriptors, SPD, T, TIS, R1, and R2, was defined through extensive survey and consultation. These descriptors may differ based on the current application of the Personnel Deployment Strategy. The implications and implementation of operation description consistency, however, remains the same.

D.2 Performance Metrics Aggregation Techniques

In development of the Technician Proficiency Matrix, a discussion is necessary on where the inclusion of domain knowledge and weighting preferences is appropriate. Throughout the Technician Proficiency Matrix calculation, there were multiple instances of aggregation identified where these preferences could be applied. The following six (6) aggregation processes were identified:

1. Technician performance sub-metrics from individual work order performance sub-metrics
2. Normalized technician performance sub-metrics from non-normalized technician performance sub-metrics
3. Normalized technician performance metrics from normalized technician performance sub-metrics

4. Normalized technician work order proficiencies from normalized technician performance metrics
5. Normalized technician attribute proficiencies from normalized technician performance metrics
6. Normalized technician overall proficiencies from normalized technician performance metrics

While it is understood that processes 1 and 2, currently calculated through simple averaging and standardization, have the capability of allowing for user specific preferences, these adjustments are considered out of scope for this research. Additionally, it is believed that an operations manager and/ or director would not want to affect calculation at such a granular level. As such, potential refinements to the remaining processes with regards to weights are discussed below.

It must be noted that the following discussion of simple weighting is one of many different alternate aggregation techniques which may be used. Two of these additional techniques that may be applicable are frequency weighting and data envelopment analysis. Frequency weighting would mainly be used to give more prevalence to technician performance metrics on those work order types they complete with a higher frequency. Data envelopment analysis would mainly be used to give more prevalence to a technician's best performance metrics for calculation of relative metrics and proficiencies. While each of these two methods may hold potential in refining the performance metric and technician proficiency calculation, they are considered out of scope for this research.

D.2.1 Simple Weighting

Simple weighting adjustment, as proposed for this research, is described as a re-distribution of metric aggregation coefficients to give greater impact to one or more metrics over others, provided the sum of the respective coefficients remains equal to 1. An example of this adjustment can be seen in process 3. The normalized technician performance metric A_{ij2} is calculated according to the following equation:

$$A_{ij2} = \sum_{m=1}^{4} t_{ij}^{m} T_{ij}^{m} \text{ for } j = 1, 2, 3, 4, \text{ and } 5 \text{ and } i = 1, 2, \ldots I$$

This calculation currently assumes the following: $t_{ij}^{1} = t_{ij}^{2} = t_{ij}^{3} = t_{ij}^{4}$ and $\sum_{m=1}^{4} t_{ij}^{m} = 1$. If, however, the operations manager knows that T_{ij}^{2} is much more important than T_{ij}^{1} in determining a technician's timeliness performance metric, they may make the following adjustment: $t_{ij}^{1} = 0.1$, $t_{ij}^{2} = 0.4$, $t_{ij}^{3} = 0.25$, and $t_{ij}^{4} = 0.25$ where $\sum_{m=1}^{4} t_{ij}^{m} = 1$. Even further modification may be made by specifying different weights depending on the jth work order type.

For processes 3 through 6, the following simple weighting adjustments may be made to incorporate domain knowledge and/ or specific user preferences:

3. Adjustment of individual q_{ij}^{m}, t_{ij}^{m}, e_{ij}^{m}, d_{ij}^{m}, tcr_{ij}^{m}, and/ or tbc_{ij}^{m} such that, for j = 1, 2, 3, and 5, $\sum_{m=1}^{1} q_{ij}^{m} = \sum_{m=1}^{4} t_{ij}^{m} = \sum_{m=1}^{7} e_{ij}^{m} = \sum_{m=1}^{4} d_{ij}^{m} = \sum_{m=1}^{2} tcr_{ij}^{m} = \sum_{m=1}^{3} tbc_{ij}^{m} = 1$ and for j = 4, $\sum_{m=1}^{2} q_{ij}^{m} = \sum_{m=1}^{4} t_{ij}^{m} = \sum_{m=1}^{7} e_{ij}^{m} = \sum_{m=1}^{4} d_{ij}^{m} = \sum_{m=1}^{2} tcr_{ij}^{m} = \sum_{m=1}^{3} tbc_{ij}^{m} = 1$.

4. Adjustment of individual a_{ij1}, a_{ij2}, a_{ij3}, a_{ij4}, a_{ij5}, and a_{ij6} such that $\sum_{k=1}^{6} a_{ijk} = 1$ for j = 1, 2, 3, 4, and 5.
5. Adjustment of individual a_{i1k}, a_{i2k}, a_{i3k}, a_{i4k}, and a_{i5k} such that $\sum_{j=1}^{5} a_{ijk} = 1$ for k = 1, 2, 3, 4, 5, and 6.
6. If calculating D_i from B_{i1}, B_{i2}, B_{i3}, B_{i4}, and B_{i5}, then adjustment of individual b_{i1}, b_{i2}, b_{i3}, b_{i4}, and/ or b_{i5} such that $\sum_{j=1}^{5} b_{ij} = 1$. If calculating D_i from C_{i1}, C_{i2}, C_{i3}, C_{i4}, C_{i5} and C_{i6}, then adjustment of individual c_{i1}, c_{i2}, c_{i3}, c_{i4}, c_{i5}, and/ or c_{i6} such that $\sum_{k=1}^{6} c_{ik} = 1$

D.3 Task-to-Team Assignment Integer Programming Formulation

With sufficiently comprehensive data quality practices in place and generated technician performance metrics and proficiencies, the development of a task-to-team assignment integer program may be attempted. The goal of the proposed integer program is to optimize the overall performance of all teams against the tasks they are assigned to complete. By using technician performance metrics as parameter input, it may be inferred that the goal is to maximize the total performance aggregate of individual assigned teams.

This, however, is not a simple matter of assigning technicians to teams and maximizing the team performance for a given task. If this were the case, there would be nothing to prevent one team from having a relatively high team value, i.e. the best technicians, and another team having a relatively low team value, i.e. the worst technicians. When creating the task-to-team assignment integer program, the generated solution should not yield teams that significantly suffer due to the goal of maximizing team performance. Therefore, the maximin programming technique is introduced.

Per Shogan 1988, “We illustrate one last “trick” for converting an apparently nonlinear problem into an LP [linear program]. In particular, we consider a decision problem with a maximin objective function – that is, an objective function involving the maximization of the minimum of several linear functions.”[111] In using maximin programming, generally, the integer program can be manipulated in such a way as to maximize the minimum team performance among all assigned teams. This creates the situation in which no one team is disproportionately worse than any other team in terms of the performance aggregate. This procedure does, however, have a potential downside.

Usage of the maximin programming approach often results in relatively homogenous output. This outcome on its own is not necessarily disadvantageous. But, by creating a homogenous set of assigned teams, it potentially precludes the generation of extremely gifted teams. Given the alternative, however, relatively consistent team performance aggregates are a satisfactory outcome.

An additional benefit of maximizing the minimum assigned team performance is in inspiring cross learning of performance metrics and attribute and work order proficiencies. It is projected that there will be many situations where technicians deficient in one area will be assigned to a team with technicians that are proficient in the same area. Simply put, when a technician with a poor performance metric or attribute and/ or work order proficiency is assigned to a team, another technician must be assigned to balance out that respective area as the objective is to maximize the minimum team performance aggregate.

The following sections illustrate the most basic formulation of the proposed task-to-team assignment integer program. The standard modeling approach is illustrated in detailing the modeling assumptions, objective statement, parameters, decision variables, and basic constraints. Appended to the formulation is a discussion of more complicated constraints and scenarios to consider in the future.

D.3.1 Assumptions

1. All technicians must be assigned to at least one task
2. Assigned tasks must have a team of 2 or 3 technicians
3. All technicians have applicable A_{ijk} for all j = 1, 2, 3, 4, and 5 and k = 1, 2, 3, 4, 5, and 6
4. All technicians have applicable B_{ij} for all j = 1, 2, 3, 4, and 5
5. All technicians have applicable C_{ik} for all k = 1, 2, 3, 4, 5, and 6
6. All technicians have applicable D_i

One item of note is about the data required for the task-to-team assignment integer program. There are only two separate pieces of data required: 1) holistically generated Technician Proficiency Matrices for each technician (A_{ijk}, B_{ij}, C_{ik}, and D_i) and 2) an applicable task list with categorization of work order type (E_n). It is assumed that each of these is available for execution of the integer program.

With respect to individual data fields in the i^{th} technician's Technician Proficiency Matrix, the integer program should interpret #N/As values as 0 values. This essentially means that, if a technician has a #N/A performance metric or proficiency, it is interpreted as the average of all technicians for that respective metric or proficiency. For example, if the i^{th} technician's A_{i55} is #N/A, the integer program will interpret this value as 0, i.e. the average technician's performance metric of the 5th attribute type and 5th work order type. Consequently, this has a marginalizing effect in the integer program as that technician is seen as no better and no worse than any other technician for that performance metric or proficiency, as they do not have the data to support either conclusion.

D.3.2 Proposed Model

Objective Statement

$$\max \frac{1}{6}\sum_{p=1}^{6} S_p$$

Parameters

$A_{ijk} \equiv$ performance metric for the k^{th} attribute and j^{th} order type for the i^{th} technician,

where $i = 1, 2, \ldots, I$, $j = 1, 2, 3, 4$, and 5, and $k = 1, 2, 3, 4, 5$, and 6

$B_{ij} \equiv$ work order proficiency for the j^{th} order type for the i^{th} technician,

where $i = 1, 2, \ldots, I$ and $j = 1, 2, 3, 4$, and 5

$C_{ik} \equiv$ attribute proficiency for the k^{th} attribute for the i^{th} technician,

where $i = 1, 2, \ldots, I$ and $k = 1, 2, 3, 4, 5$, and 6

$D_i \equiv$ overall proficiency for the i^{th} technician, where $i = 1, 2, \ldots, I$

$E_n \equiv$ order type of the n^{th} work order to be scheduled

where $n = 1, 2, \ldots, N$

Decision Variables

$$T_{in} = \begin{cases} 1 \text{ if the } i^{th} \text{ technician is assigned to the } n^{th} \text{ work order} \\ 0 \text{ otherwise} \end{cases}$$

Basic Constraints

(min technicians) $\sum_{i=1}^{I} T_{in} \geq 2$ for $n = 1, 2, \ldots, N$

(max technicians) $\sum_{i=1}^{I} T_{in} \leq 3$ for $n = 1, 2, \ldots, N$

(min tech assign) $\sum_{n=1}^{N} T_{in} \geq 1$ for $i = 1, 2, \ldots, I$

(min team Q) $S1 \leq \sum_{i=1}^{I} A_{iE_n 1} T_{in}$ for $n = 1, 2, \ldots, N$

(min team T) $S2 \leq \sum_{i=1}^{I} A_{iE_n 2} T_{in}$ for $n = 1, 2, \ldots, N$

(min team E) $S3 \leq \sum_{i=1}^{I} A_{iE_n 3} T_{in}$ for $n = 1, 2, \ldots, N$

(min team D) $S4 \leq \sum_{i=1}^{I} A_{iE_n 4} T_{in}$ for $n = 1, 2, \ldots, N$

(min team TCR) $S5 \leq \sum_{i=1}^{I} A_{iE_n 5} T_{in}$ for $n = 1, 2, \ldots, N$

(min team TBC) $S6 \leq \sum_{i=1}^{I} A_{iE_n 6} T_{in}$ for $n = 1, 2, \ldots, N$

D.3.3 Consideration of Specialty Constraints & Scenarios

D.3.3.1 Technician Assignment Restrictions and Task Prioritization

In the basic formulation of the task-to-team assignment integer program above, all tasks are assigned teams regardless of technician availability. It may, eventually, become necessary to restrict the total amount of assignments per technician due to concerns of daily availability, fatigue/ overwork, and/ or vacation or paid time off. Caution must be taken with this approach, however, as restricting the total number of technician assignments may lead to infeasible solutions. If the number of total technician assignments required is greater than the total number of technician assignments available, infeasibility will occur. The model may need to be adjusted to allow for some tasks to remain unassigned.

In discussion of allowing some tasks to remain unassigned, how to select these tasks must be addressed. A practical solution may be to first expose the applicable task list to a prioritization heuristic which evaluates risk, cost, and/ or inconvenience of not assigning a task for completion. By prioritizing and eliminating non-critical tasks from the task list, the task-to-team assignment integer program may still be applicable as is, i.e. assign teams to all tasks rather than limit technician assignments. Yet, complications may still exist if there are many more critical tasks than available technicians.

D.3.3.2 Basic Certification Requirements

An addition to the basic constraints listed above may be the inclusion of assignment restrictions based on certification status. Certification status, as briefly mentioned in Appendix B.8, may be approximated with the i^{th} technician's TBC performance sub-metrics and metrics. It is easy to create constraints in which a technician that has not achieved a TBC performance sub-metric or metric threshold would be barred from assignment to the respective work order type.

However, to restrict technician assignment based on specific training/ certification task completion requires further development of the task tracking methodology. Currently, when the TBC performance sub-metrics and metrics are calculated, they become blind to which specific tasks have been completed. Effectively, this information is lost when calculation is complete. Therefore, to expand certification restriction to individual training/ certification tasks, the links between performance sub-metrics and metrics to the respective completed training/ certification tasks must be refined.

D.3.3.3 Work Order, Attribute, and Overall Proficiency Requirements

It may become desirable to include additional constraints which restrict task-to-team assignment based on minimum required team proficiencies. In effect, each team would have a minimum required work order, attribute, and/ or overall proficiency aggregate. These requirements could function either as simple constraints or could replace the individual performance metrics as the maximin focus (i.e. maximize the minimum of proficiencies instead of performance metrics). The latter scenario may become particularly useful if the operations manager or director incorporates domain knowledge and/ or weighting preferences in the creation of work order, attribute, and/ or overall proficiencies. In this situation, the proficiencies would closer resemble a technician's relative performance than their individual performance metrics. Therefore, the proficiencies would become a more accurate system of coefficients to the task-to-team assignment integer program and would be desirable as the focus of the maximin approach.

D.3.3.4 Minimum Ability Spread Cross Learning and Assignment Mixing

An inherent goal of the Personnel Deployment Strategy is cross learning of specific attribute and/ or work order metrics and/ or proficiencies from technician team assignments. Ideally, when a team of technicians is assigned a task, those weak in an attribute and/ or work order metric and/ or proficiency will learn from partners who are strong in that respective area.

To encourage this phenomena more directly, it may be desired to include a system of constraints which require a minimum difference in relative performance, respective to certain metrics or proficiencies. As an example, the operations manager or director may dictate cross learning of quality as critically important. They then might include a constraint requiring team assignments be composed of technicians whose total range of quality attribute proficiency is least 1 standard deviation of the relative technician performance. This particular example is easily expanded to include any individual performance metrics and/ or proficiencies and can easily be specified to the individual work order type of the task assigned. Caution must be taken, however, as it is easy to see that restricting assignments to such a degree may yield infeasibility.

Rather than enforcing minimum performance metric and/ or proficiency ranges for an assignment, it may be preferable to incorporate a technician’s assignment history and develop a system of assignment mixing constraints. Effectively, these constraints would enforce relatively unique team compositions by using parameters detailing information on historical assignments. For example, if the i^{th} technician was previously assigned a task of the j^{th} order type with the $(i+1)^{th}$ technician, the next assignment might encourage the i^{th} technician be paired with the $(i+2)^{th}$ technician for the next task of the j^{th} order type. While brief in description, it is easy to see how this technique might be expanded and morphed into a system which inspires regular uniqueness in team composition. However, it is important to note that this system of constraints may not be completely compatible with other proposed constraints and modeling techniques and must be carefully constructed.

D.3.3.5 Emergency Planning & Manager Discretion

An inevitable occurrence when completing assigned tasks is the manifestation of an emergency task. If an emergency occurs while technicians are completing tasks, the focus shifts to how resources should be re-allocated to address the emergency. In this situation, it would be wise to consider physical data such as geographical distance between individual teams and the emergency, as well as the relative priority of the tasks being completed by individual teams and the number of technicians on those teams. In reality, the act of emergency planning is viewed as out of scope of this research and would best be immediately handled by the responsible site manager.

Regarding the individual site manager, it is the view of this research that, while the outcome of the task-to-team assignment integer program might be an “optimal” solution, managers should always have the discretion to override these assignments. This capability takes advantage of the individual manager's inherent domain knowledge and experience with their teams and technicians. As such, the task-to-team assignment integer program may be viewed more accurately as a decision assistance tool to the site manager in assigning individual technicians to task teams.