A Tutorial on Quality Engineering Mitigating Drought and Flood Cycles in Tropical Savannahs

Jorge Luis Romeu, Ph.D.
Adjunct Professor, Syracuse University
Emeritus, State University of New York
https://www.researchgate.net/profile/Jorge_Romeu
Email: romeu@cortland.edu
March 26, 2025;

Summary

We discuss and describe the application of statistics-based quality engineering methods such as reliability, logistics, industrial and systems engineering, and operations research to the design, development and improvement of systems that mitigate the effects of the yearly cycles of water droughts and floods, in tropical and sub-tropical savannahs. We provide implementation examples developed, under our guidance, by our Syracuse University graduate engineering students. We expect, with this paper, to contribute to a sounder understanding and mitigation of such climate events.

1.0 Introduction

This is our fourth yearly academic paper we write, discussing the role of *Quality Engineering* (QE), a collection of methodologies that use *statistical* procedures such as *reliability, logistics, operations research* and *industrial engineering*, for mitigating adverse events on populations.

Our first paper was in written in July of 2021, and dealt with applying the *Quality Engineering Methodology* (https://web.cortland.edu/matresearch/QualityEngineeringToolsCovid-19.pdf) *to Covid-19 Systems Design and Improvement*. The second one, was written in July of 2023, and dealt with *Quality Engineering Tools for Mitigation of War Fallouts on Civilian Populations*, (https://web.cortland.edu/romeu/QualEngToolsWarFalloutMitigation.pdf) using as example the war in Ukraine. The third paper (2024) dealt with mitigating effects of war fallouts on civilian populations trapped in a *closed war zone*, such as a city under siege, where people and items (https://www.researchgate.net/publication/382489101_Quality_Engineering_Helping_Civilian_Populations_on_War_Fallouts_and_Climate_Change_1) have severe difficulties getting out, and where material aid has extreme difficulties getting in.

In all three papers, we used QE methods for the analysis of such adverse events, and for their implementation, thus providing more efficient solutions. For, QE methodologies are valuable in planning, designing, implementing, streamlining and improving effective engineering solutions, rendering mitigation procedures easier to manage and execute.

This paper, just like the previous three, pursues *three objectives*. *First*, illustrate *the use of QE methodologies*. *Secondly*, *provide practical examples of their implementation* in the mitigation of adverse consequences on civilian populations, making authorities aware of QE tools and uses.

Finally, to *showcase the good work developed by our Syracuse University graduate students* during their *MFE634* Quality *Engineering* course, that is taught every Spring (see its syllabus: https://web.cortland.edu/matresearch/MFE634SylS17.pdf) for the MAE Dept.

Said MFE634 graduate students develop every semester, under our guidance, group final projects (https://web.cortland.edu/matresearch/PastProjectTopics.pdf) examining real life problems, and implementing QE tools that provide efficient solutions for them.

In our MFE634 course we do not dwell on political causes or responsibility of the parties to these events, as our interest as engineers is to help improve the conditions of those that are reluctantly caught in the middle of said events. We follow two important educational principles: (i) Dr. John Dewey's *learning by doing theory* (https://www.pedagogy4change.org/john-dewey/) and (ii) *The Role of Engineering in* (https://repositories.lib.utexas.edu/server/api/core/bitstreams/da224561-af8b-463e-8e74-2e23e44ed263/content) *Society,* by S. Nichols and W. Weldon.

2.0 Project Topic

This project is about Quality Engineering applied to mitigating the yearly Drought and Flood Cycles in Tropical Savannahs (more information in: https://en.wikipedia.org/wiki/Tropics and https://en.wikipedia.org/wiki/Subtropics#Definition).

Tropical savannahs are common in Caribbean islands such as Cuba, in the Gulf coast of Mexico, Central and South America, in India, Indonesia and other Indian oceans islands and in African countries in the Atlantic and Indian coasts. They share yearly rain and drought seasons cycles. In the first, copious rains occur that inundate the countryside. In the second, drought season, scant rain falls, and people, cattle and agriculture suffer of the lack of water and sometimes, drought.

An input/output model determines that rainwater either moves out, or moves up, thus flooding surrounding areas, damaging property, crops, cattle and even livelihoods. The issue is to find a way for water to leave the area at the same rate that rain falls into it. However, a series of issues prevent water from such. One is that there may not be enough means (rivers, canals, etc.) to help evacuate water. Another is that there may not be sufficient gradients to quickly push the water out into the sea. Finally, there may be marshes and other difficult areas, close to the sea, that will accumulate water and block the exit of further water out of the area, thus forcing the remaining to move up (i.e., increasing their levels and thus inundating the surrounding areas).

Finally, some of the said rainwater must be stored for its use during the dry season, to ease the drought. Thence, several lakes, reservoirs, and a network of distributing canals must be built, to store and allocate the rainwater that falls during the rainy season, to users during the dry season.

The design and construction of a system that fulfills these requirements, thus forestalling the big inundations of the rainy season and the water drought of the dry one, is our objective.

3.0 General Project Preparation

In this section we overview general preparation activities for a QE project. The main *QE tools* are in PPT https://web.cortland.edu/matresearch/QualEngGralMfe.pdf, and in Sections 2.0 and 3.0 of paper https://web.cortland.edu/matresearch/QualEngToolsHurricaneMitigation.pdf, that discusses the use of QE tools to help civilians better prepare to survive natural disasters.

3.1 Our Experience in Dealing with this Paper's Topic

This researcher was born, grew up and lived until age 34, in Cuba, a tropical country, working in a farm, in the countryside, for over two years, experiencing some large floodings, as well as long droughts. And he observed how locals managed the situations, under such circumstances.

In addition, this researcher studied operations research and worked for several years as an engineer in the Department of Roads, Bridges and Railways of Cuba's Ministry of Construction, solving problems involving the construction of roads and bridges that survived the rainy season.

Our study of a nonlinear programming method for the design of the optimal bridge emplacement (https://web.cortland.edu/romeu/ProgNoLinEmpPteGvnDap.pdf), with the corresponding Fortran computer program, was published in the *Journal of the Cuban Civil Engineers* and was presented to an international conference of socialist countries, in Hungary.

3.2 QE Project Development Plan

We overview here general preparation activities for a QE project. The main *QE tools* are in the PPT https://web.cortland.edu/matresearch/QualEngGralMfe.pdf, and in Sections 2.0 and 3.0 of paper https://web.cortland.edu/matresearch/QualEngToolsHurricaneMitigation.pdf, that discusses the use of QE tools to help civilians better prepare to survive natural disasters.

The very first thing required for the development of a successful QE Project is the selection of one or more *Champions*: high level officers that will ensure the fulfilment of the QE Project Team requests and needs. In our current projects, Without *Champions* help, the QE Project team's requests and demands may be ignored.

Then, we must decide which of two types of systems we will develop. We may need to *modify and improve an existent, but inefficient system*. Or, *if said system is non-existent, we will need to create it, from scratch*. Finally, we must define, with the Champion and other project leaders, the scope of the project, and select an appropriate composition for the QE project team.

All types of systems require designing and implementing command, control and communications centers, with substations able to oversee complex operations, including redundant sub-systems to back-up possible communication failures, and maintenance capabilities to resolve breakdowns.

A solid engineering project starts by implementing a COPQ (Cost of Poor Quality), with its four categories: internal, external, appraisal and prevention themes. Said information may be obtained through a Brainstorming exercise, that helps create qualitative Ishikawa chart, that shows which factors affect the response or performance measure under study. Its respective levels eventually become the framework for more quantitative statistical procedures such as DOEs, ANOVAs, Regressions, etc.

Additional information material about key issues involved in the system is obtained from the subject-matter experts' interviews. Process flowcharts and Value Stream Maps (VSM) are built to identify system bottlenecks, non-value-added steps and other problems that can then be modified or fixed, thus improving the system operation. These tools also provide guidance as to what additional data to collect, and where and when, in the system, they should be collected.

Before starting data collection, an MSA (Measuring Systems Analysis) should be implemented, to determine if the measurements taken include undesired elements, such as operator or gage errors. Gage R&R analyses detect these problems. If a large percentage of the measurement results come from actual part variation, and only a small percentage comes from operator and/or gage errors, the MSA results are acceptable. Otherwise, we must first address the measurement system problems, retest it and once accepted, we can safely start measuring the variables.

If a system already exists and we need to improve it, we proceed with a *Six Sigma (DMAIC*) or other continuous improvement methodology. However, if a system does not yet exist, then DFSS (Design for Six Sigma) and QFD matrix cascade methodologies are used to design it.

There may be specific technical problems that we want to assess. This can be done via Design of Experiments (DOE) and hypothesis testing. Our MFE634 students present examples of such analyses, using both statistical software and Excel (when specialized SW is not available).

If there are new design aspects that did not exist before, but we want to try out, we implement a DFSS (Design for Six Sigma) or a QFD (Quality Function Deployment) Design procedure. If an existing method is proven inefficient and should be modified, the *VSM (Value Stream Map)* are implemented. First, develop the VSM for the *current state,* to assess the existing process. Then, after changes or improvements are implemented, a second VSM is developed, describing the system's *future state*. Finally, a comparison of the key process parameters, before/after changes are implemented, is undertaken, to assess that the improvements work efficiently.

Water subsystems are of importance to population subsistence. We assume that a steady flow of water to the city can be ensured. Water should be acquired, tested, stored, distributed, used and, finally, disposed of. We need to assess their safety using *SPC (process control)* statistical procedures, thence, we must develop *Sampling Plans, and Control Charts*. Water distribution requires a network of pipes, a fleet of tanks and appropriate reservoirs. Water can be used for drinking, cooking, cleaning, hospital care, and sanitation uses. After being used, water must be safely discarded or treated for safe reuse. All aspects of the support for water system operations should be taken into consideration,

Failure Modes and Effects Analyses (FMEAs) and Fault Tree Analyses (FTAs) identify the root causes of failures, possible counter measures, and some redundant procedures. FMEA and FTA should be undertaken to assess how and why systems fail, what are their consequences, and what types of preventive and corrective measures can be taken to avoid total system collapse,

Finally, *Reliability* procedures are implemented to assess how the methods can fulfill their stated functions, in time. *Reliability* measures the probability of, say, a water supply system, providing effective service for a specified period, without interruptions.

Finally, we must state, implement and evaluate the suggested solutions to problems uncovered, showing that they have improved the original system, and establishing the necessary controls for said solutions to become permanent system features.

4.0 Quality Engineering Student Group Projects

In this section we review the applications of *QE statistics-based methods* used to design and implement solutions to said *problems*. These projects were developed, under our guidance, by *MFE634 students, and are explained in detail in the PPTs*. This year, we experimented with a *new approach to teaching this course*: *apprenticeship*. Given that there were fewer students than usual, instead of forming study groups we worked with them individually. We defined a two-part project (the flood/drought yearly cycles, of Tropical savannahs). We implemented the second part (Drought), and individual students implemented the power points for the first part (Rainy Season), under our guidance, following the example and approach of our second part.

This author strongly recommends our MFE students as well-qualified Quality Engineers. Their good work demonstrates their engineering knowledge and experience. I especially commend Mr. Jake Jock who, under my guidance, developed the power point for the *Rainy Season* shown here.

4.1 Quality Engineering Project to Mitigate Floods during the Rainy Season.

During the *rainy season* floods occur when rainwater pours at a faster rate than it can be disposed of. We need to find ways of disposing of excess amounts of rainfall. Otherwise, water has only one other way to go: up (floods). There are several ways that water cannot be disposed of. One is to build enough canals, rivers, etc. that can drain the region. Another is that the gradient is not sufficient to have drainage at a speed that can match the speed rain falls. Yet another is that the water hits a zone (usually marshes) where it cannot flow fast anymore, becoming a barrier that produces a water backlog and prevents water flowing into the sea.

To counter the first problem, we need to discover the rain distribution, and the System Capability (its USL/LSL induced by existing or planned canals and rivers). To offset a low terrain gradient, we can create transitory reservoirs, where rainwater can be stored and later released at a rate that the system can process. To deal with the marshes, drainage canals can be built following South Florida's canal model, that are used to drain the excess water in the Everglades. If gradient is not big enough, use the Netherlands model of canals-wind mills, that forces rainwater out into the sea. There is also a need to plan for reservoirs that store water permanently, for its use during the Dry season, with their associated network of canals, to distribute the water to the users.

Under flood conditions, sometimes water becomes murky, making it unfit for drink, washing and other uses. In such cases, we need to contract a backup supplier from which to obtain potable and cleansing water. In such cases, we also need to establish acceptance sampling schemes for testing incoming water, and a distribution strategy. We need to survey the area to establish high grounds where cattle can be safely kept, and low grounds, that should be avoided.

Water should be classified into drinking, washing, cooking, cleaning, etc., provided separately, through different water transportation systems. We need a maintenance operation, with its crews, tools, spares, vehicles, fuel, warehouse, etc. to maintain the water and transportation systems.

An extensive FMEA study should be conducted to analyze how each part of this complex system can fail; how such a failure event can be prevented, or its damage minimized; what are the failure consequences, and how we create enough redundancy in its most crucial parts (e.g. the transport and storage equipment and personnel) so the system can continue running.

The reader can find Mr. Jock's project PPT for mitigating floods to population, farmers, cattle breeders, during the *rainy season*, in: https://web.cortland.edu/matresearch/JakeFlood2025.pdf

4.2 Quality Engineering Project to Mitigate Droughts during the dry season.

We need to classify water consumption distribution by type of user: civilians, cattle, irrigation, service, etc. We need to create a total, user distribution. Such values will determine the LSL/USL required of our Process Capability to have sufficient water to service the entire user population. We need to have different water reservoirs and distribution channels according to its use; potable water must be pure, but irrigation water does not. And we need to constantly monitor the water availability so we can foresee alternative solutions, when we expect that there will be a shortage.

We need to establish a distribution system, including allocation, and establish surveillance to prevent water theft or water leaks. Water can be sold, rationed, etc. to users, who are ranked by priority. Human consumption is first; then services (fire departments, hospitals, schools, etc.) and finally agricultural and cattle production. There must be an alternative plan to compensate lack of sufficient water, with supplier water, when there is a scarcity of system resources.

Finally, the *dry season* should be used to repair and complete the water storage and distribution (reservoirs and canal) systems, to get them ready for the next *rainy season*.

The reader can find our project PPT, for the supply of water to population, agriculture and cattle, in: https://web.cortland.edu/matresearch/JorgeDrought2025.pdf

5.0 Description of the Dry Season Power Point Sequence

There are four power points describing the Quality Engineering work during the *Dry Season*. They correspond to the *Initial Assessment*; the *Six Sigma/DMAIC*, to improve an existing but inadequate system; the *Define for Six Sigma/DFSS*, that designs a quality system that does not exist; and the *Lean/Kaisen improvement* method, that takes an existing but inadequate system and makes it better by eliminating non-value-added elements and streamlining the system flow.

5.1 Initial Assessment Power Point.

This PPT describes the Beginning of a Quality Engineering Project. It starts by describing the project topic, scope and objectives. Then, it gives a pseudocode outline of the project process. The first thing is to Brainstorm to obtain information of the possible system elements, to derive input, outputs, problems, causes, etc. which are summarized in an Ichikawa chart. With this information we create the crucial COPQ chart, which helps convince management that, no matter how costly the improvement process is, it will always be sell expensive than leaving the problem unfixed. Finally, we obtain the water consumption distribution, which we have to meet with the system's water resources and our improvement work.

5.2 Improving with Six Sigma DMAIC

DMAIC is used when the system already exists but is inefficient and needs to be improved. *Define is the initial phase*; the project is organized and the first tasks, starting with Brainstorming and interviews, to obtain valuable system information, are implemented. COPQ is developed, convincing management that spending time and resources in fixing the system is a valuable investment. Some examples of COPQ issues (canals, reservoirs, etc.) are presented.

The SIPOC model (a detailed form of the Input/Output model) is developed. We use it to obtain a balance between system parts. From all this information we develop an Ishikawa chart that reflects key factors impacting the system performance, represented by the response variable. We will use this chart, later in the project, to develop quantitative models. There are several ways to approach and solve system problems, leading to different projects. Thence, we need to assess and compare them, selecting the most cost-efficient one (best).

In the *Measure phase*, we start assessing the factors impacting system performance and decide which data to collect. First, an MSA is undertaken to ensure that measurements reflect variation in the items and not measure shortcomings. If there are operator and/or gauges issues, we need to fix them and reperform the MSA, until the measurement system is acceptable. Concerns regarding the deficient system performance are investigated further and data is collected to test hypotheses about them. Said concerns are explored by interviewing different system leaders. The results help create the Pareto Charts and FMEAs, revealing what issues are important and what causes and effects are associated with problems detected. An initial Process Capability quantifies the system inefficiency, letting us know which elements and in what quantities are now required to make the improved system more capable.

In the *Analyze phase* we finish data collection and perform statistical test to verify or discard and quantify, the hypothesis (theories) elaborated. Value Stream Map of the Current state is applied, determining problem areas, bottlenecks, non-value-added steps, etc. that need to be resolved.

In the *Improve phase*, we develop possible solutions to the problems detected again using a PPI method to assess, compare and select the best. We then experiment with various solution designs of canals (dimensions, bottom designs) via DOE experimentation. We detect significant factors and their effects on a response variable, correlated with the system efficiency. FEMECAs, now including a Criticality component, allows failure comparisons, to determine which one is more important. Control Charts allow us to determine that the system is stable, and an Improved VMS shows how the proposed system changes have improved it. Finally, a maintenance organization with personnel, tools, spares, warehouses, etc. is necessary to preserve the system operation.

The *Control phase* completes the improvement work. As things have changed, new MSA, SPC and Process Capability analyses are required to assess and quantify the improvement that has occurred. LSL and USL are determined by the number and configuration of reservoirs and canal networks. And we perform final statistical analyses, to confirm the size of the improvements.

5.3 Designing Systems with Six Sigma DFSS

The *System does not exist and must be first designed*. Thence, we need to apply Six Sigma in a different way. The first three phases (Define, Measure, Analyze) are like those in DMAIC. But the final two phases (Design and Verify) are not.

In the *Define phase* we review the different uses of water and the different sources according to the different stockholders, find the Champion, implement the COPQ, form the project team, and review in detail the Quality Planning steps. In the *Measure phase* we determine the rain and user consumption distributions. These serve to establish the size and number of reservoirs and canals required to fulfill customer needs, during the Dry Season, as well as to establish the Input/Output (rain and drain) requirements to get rainwater out, before it starts flooding the region. With this, the current Process Capability is obtained, and the requirements to improve it are analyzed.

To prepare for data collection we implement an MSA, through a Gage R&R analysis, to be sure the measurements are accurate. An FMEA is implemented on the current system to ascertain the possible failures, its causes, impacts and contingencies. With such information we implement the Pareto and Ichikawa Charts and use the acquired knowledge to initiate the *Analyze phase*.

The system does not yet exist, so we need to compare potential designs. How many reservoirs, of what size and type, are needed to satisfy system needs? To evaluate them physical prototypes or computer simulation models are built and operated. Also, another FMEA is undertaken that helps determine shortcomings, bottlenecks, design mistakes, etc. Finally, the final design is selected.

In the *Design phase*, and using the QFD Matrix Cascade approach, the entire system is designed and assessed. We verify that the Input/Output rainfall model (rainwater can be evacuated before water starts backing up, flooding the region) is working. Then, consider an alternative Plan B: contracting a supplier, for the case water gets so murky that it cannot be consumed for drinking purposes. This generates two additional activities: acceptance sampling for potable water, and a procedure to distribute water efficiently, among the civilian population. Finally, a maintenance organization with personnel, tools, spares, warehouses, etc. is necessary to preserve the system.

In the last *Verify phase* the final MSA, FMECAs and Process Capability analyses are undertaken. FMECAs help identify and modify riskier design components, and the Capability shows the level of improvement the system has achieved. Finally, full system deployment is undertaken, and its documentation and detailed Gann charts are delivered.

5.4 Lean and Kaizen improvement projects

Lean and Kaizen techniques are used for **i**mproving Systems, by Eliminating Non-Value-Added Steps and by Streamlining its Flow. They accomplish this by fighting eight key system wastes. Some specific examples of such waste, and their implications, are provided. Kaizen (continuous improvement) principles include removing non-value-added activities, and inconsistent use and excessive demands, on people and processes. The Five Whys and the Five S procedures are then presented, with practical examples. They help uncover and fix many systems problems.

Initial Process Capability and SPC Charts are used to assess the system performance. Both show how unsatisfactory the system is, thus requiring improvement. Searching for the causes include Brainstorming and building of Ichikawa charts, which then become regressions. These provide initial performance values, that will be improved. We then implement the *Current State* Value Stream Map (VSM) that describes how the system operates. We can establish some hypotheses about what the causes of some of the problems are.

Confidence Intervals for Reliability of the system operation (also known as *Quality on Time*) are obtained. These allow us to establish *Mission Times* (desired times to accomplish system tasks) and their optimistic, average and pessimistic estimations.

With all these facts we implement improvements and build a *Future State* VSM that allows the establishment of a new system performance and shows the areas and extents of improvements. The improvements are verified through statistical tests and recalculation of Process Capability. Also, as the process has changed, FMEAs and MSA analyses are also required. A maintenance organization with personnel, tools, spares, warehouses, etc. is necessary to preserve the system

Finally, it is worth noting that even when Lean and Six Sigma improvement procedures can be applied separately, applying them in tandem is much more beneficial. Lean eliminates waste and streamlines the system operation. Six Sigma optimizes the system operation by minimizing its performance variation. Lean, by itself, does not deal with variation. And Six Sigma will optimize a system that may include waste. It is more efficient to implement them together.

6.0 Discussion

Our current research deals with *the application of statistical-based quality engineering methods*, such as reliability, logistics, industrial and systems engineering, and operations research, to the design, development and improvement of systems *for mitigating the yearly drought and flood cycles*, that occur in Tropical Savannahs.

There are several important issues in QE projects that deal with water distribution. There must be a distribution system to allocate water among the population, farmers, cattle breeders, etc. Water may be rationed, sold, equally allocated, etc. Bad actors, such as water thieves, will try to violate the distribution methods. Thence, we also need law enforcement to maintain order.

We also need to be vigilant about contagious diseases such as cholera, polio, diphtheria, etc. that occur when water is scarce or rationed, and hygiene suffers. Sampling the population is a valid alternative to complete inspection when we do not have sufficient time or resources to check everybody. Using an approach akin to *rectifying inspection*, we can examine members in a pre-selected sample. If any member shows symptoms of a contagious disease, we separate and treat said individuals, to prevent starting an epidemic. And if the number is high, we know that the threaded contagious disease has arrived.

A secure and efficient command and control center is key to project success. Computers can be our primary system. A backup system, for the case the primary one goes down, is also necessary. For example, cell phones can be back-up. Rapid communication enhances system efficiency. For example, knowledge of a damaged canal or reservoir would not only save lives (preventing a flood) but also improve project effectiveness (by fixing the problem, in time).

It is also necessary to find funds to support all these activities. The proposed system is expensive, and management will be adamant to provide said funds. But we can show, through COPQ, that yearly flood and drought damage, counted in lives and materials, are much more expensive.

Finally, these projects show how graduate engineering students can examine and solve real-life problems. Such experience alerts them to their societal engineering responsibility, and provides them with additional application fields, where they can employ their engineering expertise.

5.0 Conclusions

Our current objective is to alert potential disaster relief organizations and government agencies about QE techniques that can be employed, and about the types of professionals required to help relief organizations improve systems. QE techniques can help in designing, implementing and improving effective solutions to the yearly Flood and Drought issues. Readers requiring further information about these projects or QE techniques can contact us.

We also want to encourage disaster relief organizations and government agencies to undertake joint work with quality, reliability, logistics, and industrial/operations research engineers, and to apply their methods, not only after said water relief and disaster systems have been designed and implemented, but also during the time that these types of systems are being considered.

We also want to provide practical examples to subject-matter researchers, government officers, and to the public, to help them understand what quality engineers do, and how these can help set and/or improve disaster mitigation systems, thus fostering greater collaboration.

Finally, this statistics-based research on mitigation of the effects of floods and droughts, can be used as part of a general disaster relief course, or as part of an applied modeling and analysis graduate course in industrial and systems engineering, operations research, or applied statistics.

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About the Author (https://web.cortland.edu/romeu/):

Jorge Luis Romeu is an Adjunct Professor in the Mechanical and Aerospace Engineering Dept., Syracuse University (SU), where he has taught, for over 20 years, Statistics and Quality graduate engineering courses. Romeu was, for sixteen years, an SU Research Professor, and is a Senior Speaker Specialist for the Fulbright Roster Program. Romeu retired Emeritus from the State University of New York (SUNY) and worked as Senior Research Engineer for the Reliability Analysis Center (RAC), an Air Force Information and Analysis Center operated by IIT Research Institute (IITRI). Romeu received seven Fulbright assignments: for Mexico (3), the Dominican Republic (2), Ecuador, and Colombia. Romeu teaches yearly workshops in New York City, on Quality Engineering, in Spanish, for Latin American professionals. He holds a degree from the University of Havana, and a Ph.D. in Industrial Engineering and Operations Research, from SU. Romeu is a Chartered Statistician Fellow of the Royal Statistical Society, and a Senior Member of the American Society for Quality, where he is a past Regional Director, holds Reliability and Quality Certifications, and is a Member of the American Statistical Association. Romeu created and directs the *Juarez Lincoln Marti (JLM*, https://web.cortland.edu/matresearch/) *International Education Pro*ject, which has supported higher education in Ibero-America for over 30 years. The JLM Project supports the *Quality, Reliability and Continuous Improvement Institute (*QR&CII), an applied statistics and operations research free access web site that can be found in: https://web.cortland.edu/romeu/QR&CII.htm