Empirical Model Relating Chloride Loading Density and Conductance for Prediction of Galvanic Corrosion

Models and Simulations as Boundary Objects in Infrastructure Construction and Maintenance

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By
Trevor James Eggleston

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Technical Team Members:
Matthew Barbieri, Spencer Blankenship, John Emery

On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

ADVISORS
Kent A. Wayland, Department of Engineering and Society
Richard Martukanitz, Department of Materials Science and Engineering

General Research Problem:

Improving Organizational Effectiveness with Predictive Modeling

How does predictive modeling allow organizations to work more effectively, both in material results and in aiding interactions between different organizational components?

Introduction

In recent decades, predictive modeling has become a cornerstone of modern engineering practice. The widespread adoption of computers and data science techniques allows nearly any engineer to test their designs before implementation. Perhaps more importantly for critical applications, predictive modeling allows one to predict how and when a structure, component, or assembly will fail by various modes, such as mechanical fatigue or corrosion. In doing so, designers are able to make rapid, intelligent decisions that reduce the need for over-design while also optimizing designs for the most desired parameters.

Corrosion is one research area of materials science and chemistry where predictive modeling is applied liberally. By simulating and monitoring corrosive processes, more effective maintenance procedures and mitigation methods can be developed. When developing simulation models, large data sets that draw correlations between various parameters of a technical system are often required to have any predictive power. The technical study will correlate two environmental parameters (conductance and chloride loading density) relevant to predicting and monitoring galvanic corrosion in real environments.

Predictive modeling also has the ability to aid in communication and learning between engineers and other professionals. In this case, models serve as a "boundary object" between two parties of human actors. Often, there is friction between engineers and non-technical professionals regarding what constitutes necessary design or maintenance decisions. Here, predictive modeling can act as a means to convince management or government planners that such technical implementations are worth financial and time investments. The STS research project will further examine this actor network between engineers, non-engineers, and predictive models, as well as further illustrate the implications of models in this role.

The technical topic of corrosion modeling and STS research topic of modeling as a boundary object are intimately connected by the fact that predictive modeling can be shown as not only a powerful design utility, but also a powerful social one. Though the technical topic is focused on marine-environment military applications, the same principles of organization can be easily translated to civilian applications of predictive modeling such as public infrastructure projects.

Empirical Model Relating Chloride Loading Density and Conductance for Prediction of Galvanic Corrosion

How are conductance and chloride loading density correlated in galvanic corrosion involving real environments?

Modern engineering practice often employs multi-material systems in order to optimize both cost and mechanical properties. However, electrical contact between two different materials with significantly different electrical potentials for corrosion often results in an electrochemical effect called galvanic coupling. Galvanic coupling manifests as enhanced corrosion rates on the more anodic (thermodynamically favorable for oxidation) material and slowed corrosion on the more noble (thermodynamically unfavorable for oxidation) material (Oldfield, 1988). Wet surfaces, such as those made by precipitation in outdoor environments, can provide the electrical connection needed for galvanic corrosion to proceed. This type of corrosion is common in aerospace applications, where low-density noble structural materials are joined together mechanically by fasteners made of high-strength, anodic materials (Melhem et al., 2014). Corrosion in these critical applications can intensify stresses beyond what is designed and reduce structural strength, leading to catastrophic failures that end lives and cost millions of dollars. Predicting the progression of galvanic corrosion can be quite difficult, as geometries and environments of real engineering systems are often much more complex than laboratory models. Extensive work into creating numerical prediction methods of this corrosion type has been and continues to be performed globally.

Luna Labs has developed an *in-situ* sensor named Acuity™ that measures several parameters important to the study of galvanic corrosion in real systems. These parameters include those related to environmental conditions such as temperature, relative humidity, and conductance of electrolytes present. The sensor is also capable of measuring the rates of free corrosion (one engineered alloy corroding alone) and galvanic corrosion. Using these sensors, corrosion measurements can estimate corrosion magnitudes of a system. Additionally, environmental parameter measurements can be applied to a finite-element method (FEM) to build a predictive model of the spatial distribution of corrosion in a structure. While relationships between many of these variables are available in the literature, such as between solution conductivity and relative humidity (Bryan et al., 2022), certain correlations between environmental parameters needed to build FEM models are lacking. Notably, correlation between the conductance (G) and chloride loading density (LD) in marine environments are only in their preliminary stages. A quantitative relationship between these two variables could yield powerful results, such as increasing the predictive power of FEM models to aid in prevention, maintenance, and intelligent design choices with regard to corrosion damage.

Thus, the goals of this project include analyzing previously collected sensor and chloride loading density data to find empirical and quantitative correlations. While the exact methodology of our research is yet to be decided, we do have a general idea of what will be done to answer this research problem.

Methods

The first part of this project requires an analysis of a large database of environmental data collected previously by Luna Labs using their Acuity sensors. Empirical relationships between different corrosion parameters will then be determined with known chloride loading densities and those found in literature. Our team will utilize a scaffolding approach to first find the G-LD correlations in data collected in laboratory conditions, then we will advance to analyze outdoor exposure data that is less controlled and represents a more realistic corrosion environment. The LD data in the database was collected in a cumulative manner using "wet candle" devices, so we will have to back-calculate instantaneous LD values in order to make correlations for modeling. Additionally, wind speeds in an outdoor environment can be correlated with chloride loading density and to conductance. Code will be be created in Python to clean and analyze the data using machine learning techniques such as multiple regressions, decision trees, and neural networks.

After correlations have been made between the variables of interest, we verify our models through experimentation. Experiments will first be carried out in a laboratory environment inside controlled humidity chambers on real galvanic couple coupon samples. Salt will be applied in a controlled fashion using aerosol sprayers, and images will be captured to analyze the salt application and corresponding droplet size and distribution. We will then expose corrosion samples to outdoor conditions, either in Charlottesville or in a marine environment with the help of the U.S. Navy stationed in Key West, Florida. If these experiments validate our data-derived G-LD relationships, our model parameters can be used as inputs to an FEM model for predicting galvanic corrosion in marine environments. Future work may be done to verify these FEM models before being deployed into real naval and aerospace applications.

To summarize our general project and methodology structure, pictured below is a work breakdown model of our approximate timeline and steps in approaching this research.

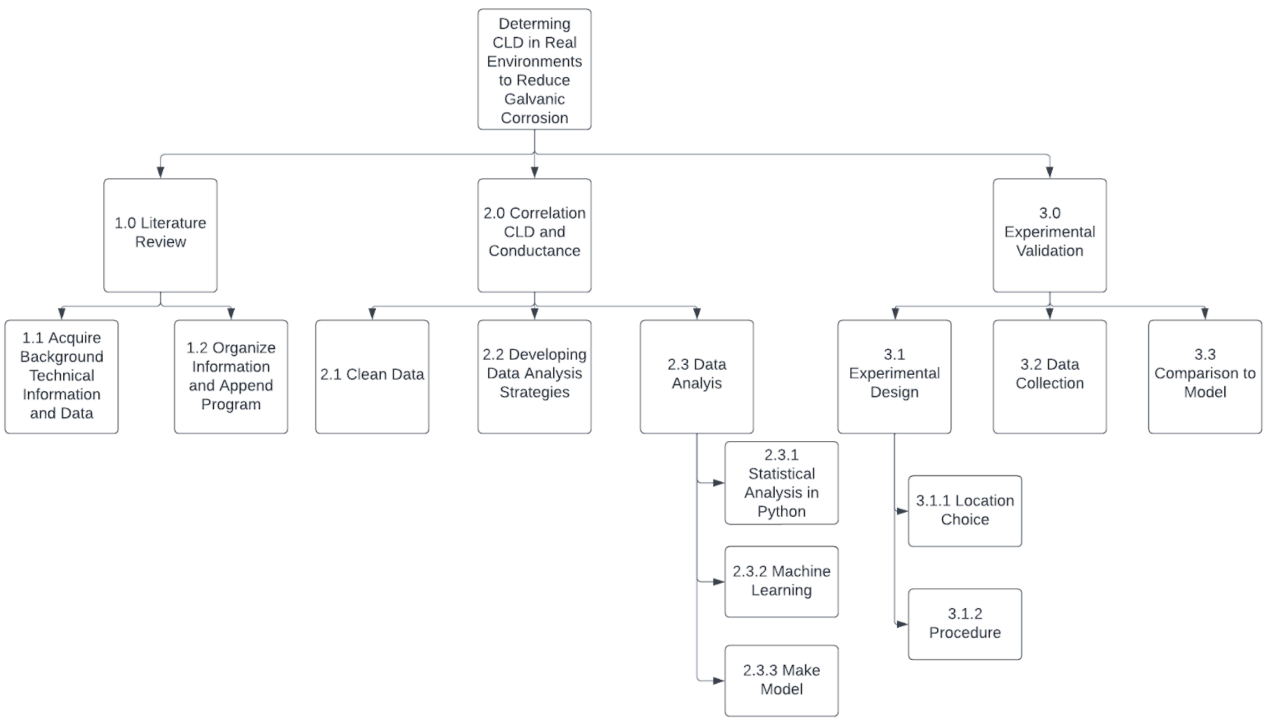

Figure 1. Work breakdown structure for technical research project

Models and Simulations as Boundary Objects in Infrastructure Construction and Maintenance

Does predictive modeling acting in the role of a boundary object between government officials and engineers working in public infrastructure maintenance lead to tangible organizational benefits? If so, by what mechanisms do they arise?

When large public infrastructure projects are being planned, government officials and workers often consider the price tag of the project as top priority. Engineers that are responsible for designing these structures and systems, however, are trained to regard the safety and quality of their designs as the most critical consideration. This conflict of priority has the potential for a tug-of-war between these two professional groups. Government planners may lack technical knowledge to appreciate safety features in design and judge if they are worth the increased cost. However, engineers may be prone to over-designing for safety and ballooning the project budget. In light of this friction, predictive modeling not only acts as a necessary design implement, but also as a potential way to mediate the two groups of stakeholders.

Background

Predictive modeling of structure-degrading processes allows engineers to make informed design decisions when considering infrastructure lifespan criteria, preventing over-design and helping mediate the two parties responsible for project completion. When building these models, valid empirical data must also be available for the models to be trained to predict the future. This data may be collected in-situ or in a laboratory. The supply of computing power and data has rapidly grown in recent decades to satisfy the technical demands of predictive modeling (Bukhsh & Stipanovic, 2020), and new statistical/numerical methods are constantly developed to gain an edge in predictive power. All actors in the social network formed when carrying out infrastructure projects must be convinced of the predictive model's accuracy and precision, and the aforementioned quality of data and methods gain further importance beyond the technical problem.

This research project will examine how these two groups (government planners/management and engineers) interact when planning public infrastructure projects and the role of predictive modeling as a translator and negotiator that enables communication between the actor groups. The goal of this research is to determine if modeling has the ability to make the bureaucratic machinery behind infrastructure and other public engineering projects work more smoothly (which may manifest in lower budgets or shorter construction times), as well as the mechanisms by which this occurs. Through critical examination of the potential advantages of modeling in technical organizational systems, and how these advantages are derived, other systems that may be optimized by this application of modeling can be identified and supplemented accordingly.

Literature Review

Models can serve a variety of roles, both in the design process and in communication. Dodgson et al. (2007) examined how the engineering profession and its practices have changed due to the popularization of digital modeling of physical systems. Three particular uses of digital modeling, which they call "innovation technology" (IvT), are defined: I) judgment and validation, II) new combinations of technology and components, and III) design conversations. Most importantly for this project, the "design conversations" section states that modeling allows engineers of different disciplines to collaborate more closely and to communicate design decisions with policy-makers and management, particularly by using visual modeling.

The idea that models can connect different social actor groups is a not new one. Bayer et al. (2014) present simulation models as interfaces that can serve several different social roles. When serving these social roles, these models facilitate group learning among stakeholders that vary by expertise and backgrounds. Four basic social roles of models are identified, and it is explained that the social role of a model may change with time. Of the four roles, we will most examine the role of models as boundary and technical objects, which "helps to transmit information between group members by demonstrating already existing knowledge and by giving group members lacking this knowledge the opportunity to engage with the system." (p. 128, Table 7.1)

Identification of tangible benefits of predictive modeling is complicated by several confounding factors in infrastructure planning and construction, with the intricacies of social behavior within structured organizations being one of them. Flyvbjerg et al. (2002) conducted a large statistical study on cost inaccuracies in public transportation projects. Notably, the cost of the vast majority of infrastructure projects is significantly underestimated. It was also found that the degree of cost underestimation had not improved in the 70 years prior to the study, and no new methods that would alleviate this problem appeared to help. The authors investigated several possible causes of cost underestimation, such as technical, economic, psychological, and political explanations. The authors concluded that the observed cost-estimate discrepancies were best explained by systemic deception, often made by engineers and price forecasters to satisfy their superiors and to increase the chances of the projects being started. Thus, difficulty in quantifying the usefulness of predictive modeling in this context is expected, and other confounding variables will have to be identified and controlled for this research.

Theoretical Framework

The system as described will be evaluated through the lens of actor-network theory (ANT) in order to illustrate the ability of models to persuade and inform non-technical professionals to the ideas of engineers. In simplified terms, actor network theory is a framework for studying sociotechnical systems in which actants define their problems and attempt to enlist the aid of other actants through a process of initial interest, “enrollment” into the actor network, and, finally, mobilization (Muniesa, 2015). In our case, the main actants of interest are government planners, models, infrastructure, and engineers. The engineers enlist the help of models to further enlist the help of government planners and officials in approving designs and allocating necessary funds. Traditional actor-network theory can be modified with the introduction of the concept of boundary objects, which are actants that help translate and simplify information between human parties of different expertise (Star & Griesemer, 1989). Clearly, this is the role of predictive models in our scenario, and it will be evaluated through this modified framework.

Methods

The first step in solving this conceptual problem will be to first model the system using the theoretical frameworks as described in the prior section. Next, this system model will be tested using case studies found in the literature to establish the role of models as boundary objects. Particularly, these case studies should revolve around public infrastructure construction and maintenance. Testimonials of engineers and other professionals that work on these types of projects may be employed to further strengthen our notions.

Next, an attempt to quantitatively identify tangible benefits to the use of predictive modeling in these applications will be made. Initial and final budget data for public infrastructure maintenance can be collected from local and state governments over a large time frame to find correlations between the popularization of predictive modeling in engineering practice to a reduction in budget inaccuracies. This budget data for maintenance will first be normalized for inflation and project size to allow identification of trends in maintenance efficiency over time. Statistical methods will be employed for analysis of these trends to check for statistical significance.

Conclusion

In a world that is increasingly reliant on data, computers, and models, it is of great interest to governments, corporations, and professionals to save time and money using predictive modeling wherever available. This is the direct goal of the technical research problem, where predictive modeling of galvanic corrosion in FEM models can allow aerospace engineers to make more informed design decisions and issue efficient maintenance regimes to cut on costs and improve safety. The STS research problem focuses on another potential cost saving mode of predictive modeling: aiding in communication between engineers and other professionals who approve construction budgets. It will be seen if models' role as a boundary object is able to improve the time it takes for designs and maintenance plans to be proposed and budgets approved, and if there is a cost saving measure associated with this shortening of the planning phases as seems to be indicated in the literature (Flyvbjerg et al., 2004). Thus, both areas of research seek to improve organizational performance using models, albeit by different mechanisms.

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