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A complex systems approach to studying the outcomes of initiatives supporting women engineering faculty.

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The national need to broaden participation in STEM is persistent. Significant resources have been invested into initiatives to expand the successful participation of women and ethnic minorities in STEM, yet the plethora of factors influencing their success and the challenges they face complicate the grasping of their real impact. The use of complex systems methods, informed by theoretical foundations, has the potential to contribute to a better understanding of the aspects that make broadening participation initiatives effective as well as to identify persistent barriers to their successes. This requires exploration of complex systems tools and methods and consideration of the theories explaining the systems where these problems are located.

This full research paper describes the ongoing data collection stage of a larger project evaluating the effectiveness of the NSF-ADVANCE program as an exemplary broadening participation initiative. As the ADVANCE program has now supported more than one-hundred US institution with the goal of expanding women representation in STEM careers, it offers a unique opportunity to explore the intricacies of enacting positive change for gender equity within existing complex systems. Framed theoretically under Acker's Inequality Regimes that acknowledges a variety of dimensions embedded in organizational inequality, we collect qualitative data that is later transformed into quantitative measures to be modeled through Qualitative Comparative Analysis. In this paper we describe the data collection stage, with the decision making required to transform qualitative data into quantitative measures. We offer a reflection of the challenges faced while collecting high level organizational data from publicly available data for the execution of complex system modeling.

Introduction

The national need to broaden participation in STEM is persistent [1]. Significant resources have been invested into initiatives to expand the successful participation of women and ethnic minorities in STEM (e.g., [2], [3]), yet the plethora of factors influencing their success and the challenges they face (e.g., [4 -10]) complicate the real grasping of their impact. The use of complex systems methods, informed by theoretical foundations, has the potential to contribute to a better understanding of the aspects that make *Broadening Participation Initiatives (BPIs)* effective as well as to identify persistent barriers to their successes. This requires exploration of complex systems tools and methods and consideration of the theories explaining the systems where these problems are located.

Our current project aims to advance and refine foundational knowledge in broadening participation in STEM education. We will engage in the use of complex systems theories and methods, such as *Qualitative Comparative Analysis (QCA)*, which has been extensively used in social sciences to uncover complex causes of social phenomena [11]. We envision to contribute with the mapping of the use of innovative methodologies to help refine theories for equity and inclusion that support the success of BPIs.

We build upon our own exploratory work evaluating the effectiveness of the NSF-ADVANCE program as an exemplary BPI [12]. As the ADVANCE program has now supported more than one-hundred US institution in the goal of expanding women representation in STEM careers, it offers a unique opportunity to explore the intricacies of enacting positive change for gender equity within existing complex systems. Framed within theories of organizational inequality (i.e., Acker's Inequality Regimes), we expect our exploration of innovative uses of qualitative data, QCA, and other complex systems methods will uncover factors influencing the success of large-scale initiatives and will generate tools that can benefit the design and assessment of BPIs at different scales, locations, and timelines.

This paper reports on the data collection stage of our project which focuses on the use of QCA models. Due to the heavy reliance on qualitative data we established the following research question:

> *What qualitative evidence can be collected to develop and run QCA models for evaluating the impact of ADVANCE initiatives on women faculty representation in engineering?*

Background

Prior work has demonstrated that higher education and engineering education more narrowly are complex systems [13], [14] in which individual and collective actions cannot be predicted, but drive the behavior of the system [15]. Complex systems are composed of multiple elements which interact dynamically with their environment, develop over time, and are characterized by uncertainty and complex causal relationships [15-19]. Elements of a complex system cannot be understood independently because interactions between the elements result in emergent behaviors that need to acknowledge the interdependence of elements [20], [21]. There is a need for systemic and transformational change in engineering higher education, reflected by the multitude of calls for such change made in the past decades [22]. Classical methods of reducing a complex system to focus on measuring or improving a single variable (e.g., test scores) inadequately capture the system processes and outcomes [18], [20], [22-25]. The study of the behavior of complex systems provides insights that may be overlooked or oversimplified by classical approaches [27]. Furthermore, considering engineering higher education as a complex system is essential for the development and implementation of interventions that lead to large scale systemic change [28], [29] because such a change needs to be supported by purposeful changes across multiple levels of the system [28].

In contrast to classical research methods, complex systems theory and methods offer a unique opportunity for understanding and improving systems of education [30], [31]. Complex systems are the main subject of study within complex systems theory, which has been previously applied across sciences and humanities to better understand market fluctuations in the field of economics [19], [32], improve community health outcomes in health policy contexts [33], [34], examine the application of new computational tools in nursing education [35], and model leadership decisions in educational systems [21], [36]. These prior studies demonstrate the ways in which institutional change has previously been modeled as a complex system in which a multitude of inputs can influence a variety of outputs while interacting with each other. Research regarding complex thinking in educational contexts is increasing, demonstrating huge potential for growth and a unique opportunity to identify and take on challenging problems in higher education [37].

However, the adoption of complex systems approaches in higher education research has been slow, as non-traditional analysis methods are required for implementing such inquiries (e.g. discrete event simulation, social network analysis, etc., [35]). Our study considers engineering education as a complex system *and* works to make systemic improvements by using complex systems theory. To do so, we focus our research in BPIs which are initiatives that are spearheaded within the complex system of higher education and aim to be pathways to institutional change [38].

Theoretical Framework

We frame this research within the larger context of systems thinking (e.g., [16], [22], [28], [39]), since we are trying to understand how the academic system influences BPIs rather than trying to understand the BPIs themselves. That is, instead of analyzing a particular intervention and its impact, we aim to analyze the system of factors that influence the success or failure of the BPI. To illustrate our approach, we chose to examine the specific context of ADVANCE as our exemplary BPI to inform this study and our research design. Therefore, our theoretical framing and research design considers the specific goals of ADVANCE initiatives.

To frame our understanding of the goals of ADVANCE initiatives, we will use Acker's Inequality Regimes as an intersectional theory explaining organizational inequality [40]. Acker's framework recognizes socially constructed differences due to class, gender, race, and other factors as the ***bases for inequality***, which locate lower-class, women, people of color, and other marginalized groups in limited spaces within organizations. Such organizational inequities are also influenced by the steepness of hierarchy in an organization, which denotes the ***shape and degree of inequalities***. In addition, the ***organization practices and processes*** formally and informally produce a multitude of inequalities; such practices usually follow textually informed practices, such as those of recruitment and hiring, organization hierarchies, work requirements, and informal interactions. Finally, ***invisibility and legitimacy on existing inequalities***, which refers to the degree of awareness of the inequality by members of the organization and how legitimate these inequalities are perceived to be within the organization. A thorough understanding of all these factors is critical to bolster or eradicate the persistence of existing inequalities. In the context of institutions with ADVANCE initiatives it could be expected that purposeful efforts can be derived to address each of the presented elements.

There are a multitude of factors influencing women faculty advancement in STEM. In our analysis of literature [41] (summarized in Table 1), we identify factors affecting the experience of women faculty at different stages of the faculty career, including the hiring stage, and early and late career stages. For example, lack of assessment has been addressed with strategies related to promotion policies whereas the factor of perception of TT positions has been addressed by understanding the differences of research productivity or salaries. Both factors and strategies are mapped to the tenets of our theoretical framework.

Furthermore, the basis and shapes of inequities are ubiquitous to organizations, so we represent them through inclusive expansion in both the organizations and individual experiences. For example, ample research has identified that there are policies established to minimize inequities that affect women faculty, like those related to dual hiring [6], work-life balance [8] and promotion [42]. However, there is also evidence that certain organizational dynamics hinder the actual motivation to use such policies [43], [44], [45]. Therefore, further understanding of such dynamics is necessary, and this work aims to contribute to such understanding.

Table 1. Factors identified in literature to influence women faculty advancement mapped to the tenets of Aker's inequality regimes. Modified from [40]

Career Stage	Acker's Inequality Regimes	Challenges	Strategies
Hiring	Organizing Processes	Dual Career Hiring	Dual Hiring Policies
	Invisibility of Inequalities	Perceptions of TT positions	Differences in Research productivity or Salaries
		Stigmatization	Destigmatize policy usage
Early Career Stage	Organizing Processes	Lack of mentoring	Mentoring structure and practices
	Invisibility of Inequalities	T/R/S time allocation	Perceived organizational support
		Socialization	Family Friendly Policies
		Work life Balance	Work life satisfaction
Late Career Stage	Organizing Processes	Lack of Assessment	Promotion Policies
	Invisibility of Inequalities	Gendered Socialization	
		Discouragement from promotion	Job Security

Qualitative Comparative Analysis

Although it has increased in popularity [46], Qualitative Comparative Analysis or QCA is a case-base method [47] that has been developed within the last two decades [48]. Case-based methods differ from variable-based methods such as regression, the latter typically focus on the impact an independent variable or variables have on an outcome of interest; instead, case-based methods focus on profiles (composed by many variables) how such profiles vary and how they lead to different outcomes. In that sense, case-based methods are more explanatory in nature. QCA aims to identify which profiles are associated with an outcome of interest [49], [50] using a perspective of complex causality, which acknowledges that an outcome is a result of the synergistic work of multiple causal forces in tandem [16].Therefore, a main assumption is that the variables in a case profile are too interconnected to be considered independent [51], which is opposed to variable based approaches that aim to identify a list of variables or their interactions influencing a single outcome. This approach can be acknowledged as a more realistic approach to analyze complex social systems such as institutions of higher education.

Therefore, QCA applies a set theoretic approach, in which all possible combinations of case profiles are identified and compared to an empirical set of profiles that might lead to the outcome of interest [50]. Consequently, QCA requires the use of binary indicators to describe the profiles and outcomes, to then identify the variety of factors' profiles that may lead to the same outcome.

Previous Results

We have explored the feasibility of QCA as a method to model complexity in institutional contexts striving for gains in faculty diversity in [4], where we selected cases of institutions that had different combination of relevant conditions that could theoretically lead to higher women representation. In particular, the presence of an ADVANCE program, initial critical mass of women faculty, the presence of a female leader, and source of institutional control (private or public). The outcome of interest was if the institutions under analysis had doubled the representation of women faculty during the considered period.

Our QCA execution resulted in the identification of three theoretical paths to reach the outcome of interest, which where a) institutions that had not achieved critical mass at the starting point and have not had a female leader during the considered period, b) public institutions that had not had a female leader during the considered period and have not had an ADVANCE initiative, and c) public institutions that did not have an initial critical mass but had an ADVANCE initiative [4]. From our results, since the paths towards increasing participation included those that did not have ADVANCE initiatives, we interpret that there are additional theoretical considerations that, if understood, could bring a better grasp of alternative strategies, as well as barriers to achieving the goals of ADVANCE, and other BPIs. In this research we explore such potential.

Study Design

The first stage of our project is this observational and retrospective study, in which we rely mainly in publicly available sources that will provide information about the policies, practices and narratives held by each of the selected institutions under analysis. We selected 15 public, R1 institutions that received ADVANCE grants in the first four cohorts of the program (2001, 2003, 2006 and 2008). These institutions were paired with 15 comparable public R1 institutions that did not receive ADVANCE funding. To ensure comparability, the paired institutions were matched based on enrollment size and location. The maximum difference in enrollment size between paired institutions was set at 8,000 students, with enrollment data from Fall 2022 used as the reference point. For location compatibility, priority was given to institutions within the same state. If a suitable match within the same state was not available, we selected institutions from neighboring states with similar enrollment sizes and public R1 status. This rigorous pairing process ensures a robust comparison between institutions with and without ADVANCE initiatives. We then used the selected cases to identify necessary or sufficient factors for the given outcomes [11], [52].

While we have concluded one round of data collection, at the time of writing this paper we are validating our data, to enhance the reliability of our analyses. Once all data is collected, we will execute our QCA with outcomes of interest for the cases and factors related to it. While QCA allows the study of one outcome at a time, we plan to sequentially explore multiple outcomes as result of ADVANCE initiatives. Given the ADVANCE initiatives' goal of expanding women representation in STEM, and our specific focus in engineering, we will use the following three outcomes: 1) the current ratio of women engineering faculty at an institution, 2) the number of women engineering faculty hired since 2000, and 3) measures of retention and promotion of women faculty since 2000 (used as a measure of quality of experience after hiring). Only the first one has been collected so far. We selected 2000 to be the baseline year for these outcomes because the ADVANCE program had its first cohort in 2001 [12]. In Table 1 we present the general mapping between the identified factors and the elements of our theoretical framework.

The factors that we have identified as potentially affecting the outcomes of ADVANCE initiatives is first based on prior literature, prior theory, and knowledge of the cases [52], [53] (see Table 1). Theory drove the selection of an appropriate number of factors with respect to the proposed sample size [53]. We recognize that these factors are not separate from the cases, rather the factors are aspects of the cases [49]. We use the term factors rather than variables to more closely link our QCA to the complex system property of emergence [49]. In Table 1 we present the general mapping between the identified factors and the elements of our theoretical framework.

Table 2. Factors that potentially affect the impact of ADVANCE initiatives based on theory and literature.

Factor	**Theoretical Dimension(s) (source)**
ADVANCE Grant • How long ago did they receive funds: (Never, 21 years, 18 years, 15 Years)	Organizing processes (NSF and institutional websites)
Representation of Female Faculty • Number of female leaders • Research funding for female engineering faculty • Teaching & Service loads of female faculty	Shape and degree of inequities, Invisibility of inequities (IPEDS, ASEE, public websites, etc.)
Culture of Engineering School • Ratio of female undergraduate engineering students to total undergraduate engineering students • Ratio of female graduate students to total graduate students • Engineering faculty to engineering student ratio • Gender and Racial Equity Initiatives • DEI presence on school website	Invisibility of inequities (IPEDS, websites of DEI focused initiatives, etc.)
Intersectional nature of gender inequality • Number of leaders of color • Ratio of engineering faculty of color to total engineering faculty • Ratio of engineering students of color to total engineering students • Racial equity initiatives	Bases of inequities Shape and degree of inequities (IPEDS, ASEE, public websites, etc.)
Policy • Availability and clarity of tenure and promotion process • Hiring and Mentoring policies • Parental Leave Policy	Organizing processes that create or recreate inequality (Publicly available policies)

Data Collection

The sources of this data for each institution were Engineering Data Management System (EDMS) of the American Society for Engineering Education (ASEE) [54], the publicly available Integrated Postsecondary Education Data System (IPEDS) [55], and other public sources such as institutional websites. Qualitative data, such as policies and websites were analyzed accordingly and transferred into qualitative measures for QCA. Many of the interpretations to translate the qualitative data into the dichotomous values are based in content analysis [56] and discourse analysis [57] of the raw data collected from the selected institutions.

The outcome of the data collection is a matrix where each factor has been determined for each institution to have values 0 (absent) or 1 (present). Similarly, for the outcomes of interest, they are dichotomized as 0 (absent) or 1 (present). This binary matrix, similar to a truth table, is the raw data for the QCA algorithm.

Data Collected to Date

Selected Institutions

As mentioned, we started with institutions that were granted funds for an ADVANCE initiative in their first cohort in 2001, our focus was on R1 institutions as defined by the Carnegie classification at the time of award. Since ADVANCE awards were granted in cohorts that were selected every two years, in order to reach our goal of 15 institutions we expanded to Cohort 4 (2008) for their selection. After these institutions were selected, we used data from IPEDS to identify institutions with similar characteristics in terms of location and size. We aimed to prioritize selecting comparable institutions within the same state, acknowledging that there are some characteristics in terms of policies that are dependent on the location, however that was not always possible to execute. Figure 2 shows a map of the distribution of the selected 30 institutions. Those with ADVANCE grants were denoted with green dots, while those comparable institutions without it were marked in orange dots. Names of the institutions are omitted as will be the case for any future publications.

Figure 2. Distribution of selected institutions for the study.

Outcomes of Interest

As mentioned, while we are planning for more outcomes, currently, we have collected outcome of interest *(1) the current ratio of women engineering faculty at an institution in 2023*, which was collected from the EDMS system for the institutions selected. In addition, we also collected the number of women engineering faculty, and the total engineering faculty at the time of ADVANCE grant to calculate the proportion of women faculty at time of award. This will also allow for the calculation of the change in proportion of women faculty between the time of award and 2023.

In our first explorations we defined our dichotomous variable as 1 (has doubled the proportion of women faculty in engineering) vs 0 (it has not doubled the proportion of women faculty in engineering). We previously chose “doubling” the representation of women faculty as a metric because we considered it represented substantial institutional commitment to change. However, this metric requires improvement since very small proportions might not be that difficult to double, while larger proportions are more challenging to improve. Therefore, in ongoing improvements to our work, we are planning to explore the use of a threshold, following Kanter's critical mass theory which establishes that a critical mass is needed in order to surpass the footing of a minority group in an organization, such mass can vary between 15 and 30% [58]. We are currently experimenting with different thresholds that reflect the most suitable decisions given our research goal, although we consider 20% a viable option given the national proportion of women in engineering programs.

Factors of Interest

A variety of factors were collected that will be used in the execution of QCA. For that purpose, public data sources were consulted. In what follows we describe groups of variables that have been collected to date, and the details of their processing from qualitative data to the binary variables needed for QCA. We discuss the areas of opportunity that we still have to strengthen this process, and immediate plans we have to engage in such improvements.

The ***culture of the institution*** was gauged first, by the *presence of female leaders* through different variables. First, the *number of female leaders* was measured through accessing the websites with the information for the leadership at each institution. For this, we considered leadership at the college level, as well as the institution level (president, provost, vice provost, deans, etc.). The gender of leaders was determined based on their name and picture which were most of the time available on such websites. Whenever in doubt we also explored articles and websites where the individual under consideration was referred by their pronouns. We recognize that this approach has limitations, but to this date is an accurate enough measure. Once the number of female leaders was captured and the total of leaders was captured so we could also engage in the calculation of a proportion and relate this to the concept of critical mass to decide a threshold to make turn the variable in either 0 or 1. The rationale about this variable and acknowledging Acker's inequality regime is that if a female leader is chosen for the highest leadership roles, some work and commitment in changing the shape of inequalities in the organization has already taken place.

The ***Culture of Engineering School*** was captured through many variables:

Ratio of female undergraduate engineering students to total undergraduate engineering students was calculated through accessing data from the EDMS. Since the national average of women engineering students is below or around 20% we can consider a threshold a bit above such level as the critical mass cutoff to determine if the presence of women in the field at a particular institution is improving. Such "above average" participation of women most likely reflects intentional efforts of the institution in advancing the presence of women in the field, therefore showcasing an informed and committed institution.

Similarly, the *Ratio of female graduate students to total graduate students* could be argued to be an indicator of culture just as the previously described. However, we acknowledge that the statistics at the graduate level are more stringent in terms of gender disparity. Therefore, the threshold to be considered will most likely be lower. The data for this ratio was also collected from the EDMS system.

Engineering faculty to engineering student ratio was also collected from the EDMS system. Our hypothesized relationship with the culture of the engineering school is that of lower ratios demonstrating a stronger commitment to student success as it is documented that lower ratios favor student thriving. The threshold determined to transform this variable into a dichotomous one was the recommended ratio in 2023which was 18:1 [59], all institutions that were at or below such ratio were determined as 1, those with higher ratios were determined as 0.

The *Intersectional nature of gender inequality* was acknowledged by bringing aspects of racial equity in the data collection process. In particular, the following factors:
Number of leaders of color, in a parallel fashion than that of number of female leaders, it was acknowledged that the shape and degree of inequalities is likely being addressed at the institutional level to some extent. The identification of these leaders was also conducted at the highest leadership (president, provost, vice provost, deans, etc.), and at the college level.

Parallel to the factors described before for women presence, the *Ratio of engineering faculty of color to total engineering faculty* would represent a commitment to diversification of the faculty body to serve a diversifying student body as well as the *Ratio of engineering students of color to total engineering students* could represent a commitment to advance the diversification of the field. These variables were also gathered from the EDMS system. These were originally quantitative measures that were later categorized as a qualitative variable for the purpose of recategorize as a 0/1 variable.

Finally, we took a look at *Policies* that the institution had to support the advancement of women in engineering. Many of which have been extensively documented to influence positively the success of women, in particular, we paid attention to the *Availability and clarity of tenure and promotion process*, *Stop the tenure clock policies*, and *Dual Hiring Policies*. While many of these were policies that were commonplace, we relied on the availability of these policies in their public access spaces. Therefore, we acknowledge that these might not be perfect proxies for the intended data.

Discussion & Upcoming Work

This paper reports on our identification of feasible qualitative evidence that have been collected to execute Qualitative Comparative Analysis for evaluating the impact of ADVANCE initiatives on women faculty representation in engineering. The data collection stage has been heavily invested in the selection of the institutions for the analysis and the theorizing of the variables that were feasible to be collected based on our theoretical framing. While we are advanced in the data collection stage, we are currently performing a validation to strengthen our analyses. During the execution of the data collection for the first stage of this larger project we have identified useful and public available sources to capture outcomes and factors about institutions that reflect their evolution and status based on such theories. We have proposed rationales that support the processing of raw data found in websites and other publicly available sources, to tie with the theoretical aspects related to the advancement of women faculty in engineering as shaped by Acker's inequality regimes.

Our identification of outcomes of interest have made evident that the use of the "doubling of" the number of engineering faculty is a very limited outcome to focus on, providing opportunities to improve such outcome through considerations of critical mass as a defining element in combination with the rate of increase for the gains on women faculty. Similarly, modifications to the factors of interest could be considered to improve the format of our data for the intended models.

Up to this point, the qualitative evidence collected is promising for their use in QCA models. Our work demonstrates how qualitative data from diverse sources can be systematically transformed into quantitative measures to develop and run QCA models. The next step in this study is to run the QCA models considering the multiple factors identified in this broad theoretical model. This process will allow us to identify key configurations of factors that influence the success of ADVANCE initiatives while also providing actionable insights for institutions wanting to improve gender equity in STEM faculty representation.

We plan to use the fsQCA software [60] for the execution of our models. Based on the identification of combinations of causal factors from the QCA, we will generate a preliminary theory of the systemic factors that increase or decrease the number of female faculty in engineering. The outcome of this first phase will be a list of causal links, we expect these links to include many that are already well documented in the literature as well as new ones. It is envisioned that this first modeling will provide a baseline for the second part of the project which will use the elements identified by QCA for the creation of theoretical feedback loops that will be explored through Systems Dynamics Modeling, which will complement the exploration of complex systems methods in the analysis of the impact of Broadening Participation Initiatives.

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