Diversity dynamics modeled as a complex system in institutional contexts

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***Abstract*— The purpose of this work-in-progress paper is to identify barriers and drivers occurring in academic institutions aiming to diversify their engineering faculty. We recognize that institutions of higher education are complex systems driven by a multitude of internal and external forces that play a role when trying to enact institutional change. Examples of these factors are limited resources, conflicting needs of multiple stakeholders, and different academic cultures. To better understand how these factors affect change, we consider engineering education as a complex system. In this early-stage project, we are using literature, existing theories, and ASEE data to identify causal loops that illustrate a particular space of institutional change related to faculty diversification in terms of gender, through the evaluation of the effect of ADVANCE initiatives. The goal is to explore the feasibility of using the complexity theory method of Qualitative Comparative Analysis (QCA) to identify leverage points and persistent barriers to change. We will summarize the potential of QCA as a methodology to explore the challenge of faculty diversification in STEM, and other intricate problems in higher education.**

Keywords—faculty diversity, complex systems, qualitative comparative analysis, institutional change.

I. INTRODUCTION

Institutional change can be modeled as a complex system in which a multitude of inputs can influence a variety of outputs while interacting with each other. The potential for using a complex systems framing to tackle problems in education has been recognized for some time now [1], [2]. In short, complexity theory takes complex systems as its main subject of study, a general class of systems that are composed of many elements, interact dynamically with their environment, develop and evolve over time, and are characterized by uncertainty and interwoven causal webs [3]–[5]. However challenges persist as the implementation of complex systems research endeavors require specialized methodologies [6]. Nevertheless, some tools have gained presence in the social sciences to tackle complexity. Such is the case of Qualitative Comparative Analysis, which has been extensively used in economics [7] and is growing its presence across fields.

The goal of this work in progress paper is to explore the suitability of the use of a particular complex systems method, Qualitative Comparative Analysis (QCA) to identify the variety of paths leading to significant gains in the representation of women faculty in engineering. We present an exploratory analysis with institutions from the first cohort of NSF ADVANCE grantees and their comparable institutions as a proof of concept of the feasibility of using QCA for the analysis of complex systems involved in explaining drivers for institutional change aligned with diversifying faculty in engineering.

II. BACKGROUND

A. Complex Systems In Engineering Education

During the last decades, there has been recognition of the potential of using complex systems theory to understand and improve educational systems [1], [2]. Nevertheless, it has been argued that the adoption of complex systems in educational research has been slow due to the non-traditional methods of analysis required for the implementation of complex systems inquiries (e.g. discrete event simulation, social network analysis, etc.) [6].

Furthermore, the envisioned space of inquiry for the use of complex system theory in education often focuses exclusively on the learner-level space, for example, classroom interactions and how they influence learning [5]. In a recent review of the applications of complexity theory in engineering education research [9], the authors identified a variety of topics that group existing research using complexity theory in engineering education, mainly: (1) Epistemological and ontological perspectives in engineering, (2) Complex thinking and competences, (3) Pedagogical approaches to complexity engineering, (4) Complexity-sustainability-transdisciplinary interdependence, (5) engineering axiology, and (6) systemic transformation of engineering education. Only the last group denotes the need to consider the engineering education system as a complex system with many elements interacting in order to improve it. Few efforts have been established in this space, considering the real impacts of policies at institutions [10], [11]

In this project, we are exploring the challenges of diversifying faculty in engineering as a problem within the complex system of engineering education.

B. *Faculty Diversity & Institutional Change*

The diversification of faculty in science and engineering, a pressing national need, has been stated as a goal for positive institutional change. It is expected that increasing the representation of women and racially minoritized groups at the faculty level will catalyze the diversification of STEM fields. Empirical evidence has already showcased the positive relationship between faculty diversity and student diversification and student success [12]. However, despite the existence of initiatives to promote the advancement of faculty diversity, gains have been slow. Recent data from the National Science Foundation show that while women and racially minoritized groups earn 58.4% and 21% of STEM Bachelor degrees, respectively, they represent only 34.6% and 10.1% of faculty at 4-year institutions [13]. In order to identify roadblocks as well as leverage points (i.e., factors that could have a big impact with lesser effort) that can support the diversification of STEM faculty, we need to recognize the complex interactions among a multitude of factors affecting such goals.

Extensive research has been devoted to document the challenges of women faculty in engineering, including barriers to entry to the career [14], lack of balance between teaching, research, and service [15], socialization challenges [16], lack of mentoring [17], work-life balance [18] and limited family-friendly policies [19]. To tackle those challenges, there are multiple targeted initiatives, such as the ADVANCE: Organizational Change for Gender Equity in STEM Academic Professions [20]. Supported by existing research on the challenges faced by women faculty, the goals of ADVANCE include increasing the representation and advancement of women academics in STEM through systemic approaches, promoting gender equity in STEM in innovative and systemic ways, and contributing to the creation of knowledge around equity across gender and other identities of STEM academics. To reach its goals, ADVANCE sponsors initiatives to conduct projects of institutional transformation as well as those related with adaptation of practices and sustaining change [20]. Between 2001 and 2018, ADVANCE funded initiatives at 177 different institutions of higher education spread across 47 states, including 40 minority serving institutions and 13 professional or research organizations in STEM, totaling more than $270M [20]. The empirical research produced by ADVANCE initiatives is extensive, providing evidence of the benefits derived from the different elements of such initiatives, including recruitment and mentoring programs [21], [22]. However, the literature evaluating the actual effectiveness of ADVANCE programs is limited and comes with multiple challenges [23]. In this work we are presenting an approach to capture the dynamics of gains due to ADVANCE initiatives within a complex system through the use of the Qualitative Comparative Analysis method.

C. *Qualitative Comparative Analysis*

Qualitative Comparative Analysis or QCA is a methodological approach developed by sociologist Charles Ragin [24]. QCA is associated with case-based methods [25], a broad family of techniques describing and analyzing holistic cases as the main focus of study. Case-based methods stand in contrast to many variable-based methods [25], [26], e.g., several statistical approaches like regression, ANOVA, and hierarchical modeling. Whereas variable-based methods typically center their focus on the impact an independent variable or variables have on an outcome of interest, case-based methods center their focus on cases on their profiles (which are composed of many variables) and how profiles differ between cases (more descriptive) or how different profile configurations lead to different outcomes (more explanatory). Other case-based methods include multiple or single case studies [27] and case-based modeling [26], [28].

Generally speaking, QCA attempts to find, which, if any, case profiles are associated with some outcome of interest [7], [29]. QCA is grounded in the notion of complex causality, which stipulates that a given outcome is the result of multiple causal forces working in conjunction [3]. This assumption was built into QCA to address real-world complex social systems, such as education institutions, where many interwoven factors may influence outcomes in the system. In variable-based approaches, researchers may attempt to identify a list of independent variables or interactions between variables that influence a given outcome. However, with QCA and other case-based methods, it is assumed the variables in a case profile work together and are too interconnected to be considered independent [30]. Thus, QCA uses a set-theoretic approach, identifying all possible combinations of case profiles from an input dataset and reducing this set of possible configurations to the empirical set of profiles that may or may not exhibit an outcome of interest [29]. To run QCA, case profiles must first be turned into binary indicators, which are then used in the aforementioned set operations. QCA may identify that multiple profile configurations lead to the outcome of interest, reflecting the concept of multifinality [7] or that systems with similar, but not identical profiles may lead to the same outcome. From a QCA analysis, then, the profile configurations most associated with the outcome will be identified, revealing which sets of conditions or factors are likely to lead a system to have said outcome.

A critical notion in using case-based methods in general and QCA in specific is the nature of cases. Byrne [3], [31] argues that cases themselves can be considered complex systems. That is, cases have their own boundaries, have an internal set of interacting components, have their own history, respond dynamically to their environment, and evolve or change over time [5], [31]. If cases are complex systems, this informs how case profiles are built (i.e., they are a combination of internal attributes of the system as well as environmental impacts on said cases) and has implications for how we might understand or intervene in complex systems, for example addressing piecemeal changes may be insufficient to bring desired changes if it is a conjunction of factors causing the presence or absence of an outcome.

III. Methods

Derived from our goal of exploring the feasibility of QCA as a method to model complexity in institutional contexts striving for gains in faculty diversity, we will be following the stages of the execution of QCA as presented in [32]. In general, the execution of QCA starts with the definition of a dataset, including the outcome and sets of interest, which are guided by the theoretical relationships we decide to focus on. This is, that we are defining the set of factors that are theorized to be related to the outcome of interest.

These decisions will be illustrated accordingly at every step. Once the dataset is created the execution is conducted through algorithms that identify unique paths to the outcome of interest, we then present the interpretation of such results and the future potential for QCA to model institutional change in diversifying faculty.

A. Executing QCA

1) Identify relevant cases and causal conditions: To identify which relevant cases to select, we first had to focus on the condition of having an ADVANCE program. Given that there was a large number of ADVANCE programs nationwide, we opted to select only a subgroup for this exercise. We decided to pick the first institutions awarded with an Institutional Transformation (IT) award in 2001 as published in the NSF website [20]. There were nine institutions in such group, however, some of them were not R-1 research institutions, and were removed for that reason so the cases were comparable. This resulted in a total of seven institutions for consideration.

Once this subgroup of cases was selected, we used data from the Integrated Postsecondary Education Data System (IPEDS) [33], particularly their IPEDS Data Feedback Report 2021 to explore comparable institutions for each of the seven selected institutions. IPEDS generated comparison groups for each institution based on their Carnegie Classification, control source, and enrollment of similar size. To select one counter case for each of the ADVANCE awardees we also considered geographic differences, therefore prioritized institutions that were as close geographically to the ADVANCE awardee as possible, and that were not granted an ADVANCE grant at some point in the future. This process was repeated for each institution ending in a set of 14 institutions, seven with and seven without ADVANCE.

Since the selected ADVANCE grantees received such support in 2001, the growth in female faculty in engineering was collected for the years 2001 and 2021 using the ASEE Engineering Data Management System [34]. Because gains in women faculty representation can only be gauged at the individual institutional level, the outcome we selected was the result of having doubled the representation of women faculty during that time window. Seven institutions had the outcome of doubling their representation of women during the considered timespan.

The next part of this first stage takes care of defining the theoretical relationships we want to explore, which are described next:

a) ADVANCE: institutions with and ADVANCE award are expected to be commited for their envisioned institutional transformation therefore it is expected that positive changes (i.e. gains) in the representation of women faculty will be tied to the implementation of such initiatives. The selection of institutions in the first cohort of grantees also allows to evaluate of gains that were achieved in the last twenty years for the considered institutions. The considered variable is a dichotomous variable with a value of one for those that were part of the first cohort of Institutional transformation awardees, and zero for their included counterparts.

b) Critical Mass: the theory of critical mass [35] describes groups' relationships depending on their different proportional representation within a context. Such representation evolves from uniform (composed exclusively of one type of category i.e. same gender groups), to skewed, tilted, and balanced groups (equal representation). The critical mass is the proportion of a minority group that facilitates their inclusion and active participation, and it is usually established at 15% [35]. However, none of the considered institutions had such proportional representation of women faculty in the year 2001, therefore the considered threshold was 10%. Institutions that had at least 10% of women faculty in 2001 were coded as having critical mass (one) or not (zero).

c) Female Leader: Acker's theory of gendered organizations [36], considers five processes that make organizations gendered: (i) the gendered division of labor, (ii) symbols and images that strengthen such division of labor, (iii) gendered interactions that perpetuate patterns of dominance and submission, (iv) gendered elements embedded into individual identities, and (v) gender as an essential part for conceptualizing social structures. The presence of a female leader at a university aligns with the second dimension as female leaders are a minority, and the presence of one encourages a radical change in the gender roles expected at a university and is more aligned with gender equity views. For our data, institutions in our set that had at least one female in the highest leadership position (president, chancellor) during the considered period were coded as one, with those that did not have any of such instances coded as zero. This data was collected through online searches for each institution.

d) Control: there is evidence that private and public institutions vary significantly in their hiring, tenure, and promotion policies [37]. Therefore, we consider such differences have the potential to impact the recruiting efforts of institutions. For this variable public was coded as one, while private control was coded as zero.

2) Construct the data set: The resulting dataset is presented in Table 1.

3) Examine possible necessary conditions: In this stage, we consider the conditions that are necessary for the outcome to happen, we are hypothesizing that the presence of an ADVANCE award is a necessary condition for the outcome of doubling the proportion of women faculty at a given institution. Once quantitatively analyzed through the software fsQCA [38] we find that such condition only accounts for 42% of the outcomes. However, the evaluation of possible necessary conditions requires consistency scores of at least 90%, therefore the presence of an ADVANCE initiative is not a candidate for necessity, giving evidence that the consideration of other conditions needs to be explored in tandem for particular paths leading to the gains evaluated in the outcome.

TABLE I. DATASET WITH THE DESCRIBED THEORIZED RELATIONS

CaseID	*ADVANCE*	*Crit Mass*	*Female Leader*	*Control*	*Outcome*
1	0	1	0	1	1
2	0	0	0	0	1
3	1	1	0	1	0
4	1	1	0	1	0
5	0	1	0	0	0
6	0	0	0	1	1
7	0	0	1	1	1
8	1	1	0	1	1
9	1	1	1	1	0
10	0	0	1	1	0
11	1	0	1	1	1
12	0	0	1	1	0
13	1	1	1	1	0
14	1	0	1	1	1

4) Construct the truth table and resolve contradictions: This stage of the analysis was conducted through the fsQCA software. A truth table with all the possible combinations of conditions is created and the number of positive cases (i.e. those with the outcome) are evaluated. QCA then accounts for the proportion of cases that are associated with a given path (known as raw consistency), as well as the proportion of cases that travel through that path alone (known as unique consistency).

5) Analyze the truth table: The execution of the analysis using the Quine-McCluskey algorithm in the fsQCA software resulted in three unique paths that led to a coverage of 71.4% of the cases. Each of the three paths explained two of the cases with some overlapp between them. The three specific cases are analyzed in the next step.

6) Evaluate the results: The resulting unique paths are described using boolean algebra with the considered conditions. The three identified unique paths leading to the outcome of interest in this exercise were the following:

a) ~critmass~femleader* – Institutions that had not achieved critical mass in 2001 and have not had a female leader during the considered timeframe

b) ~femleader~advance*control* – Public institutions that have not had a female leader during the considered timeframe, and have not had an ADVANCE initiative

*c) ~critmass*advance*control* – Public institutions that had not achieved critical mass in 2001 but did have an ADVANCE initiative.

Collectively, these three paths count for five out of the seven cases with a positive outcome (i.e. doubled the proportion of women faculty).

IV. RESULTS

The first path that aligns with the theoretical relations we established is path c) in which public institutions without a critical mass of women faculty manage to secure an ADVANCE grant and the combination of these three conditions can be mapped to the outcome of doubling the proportion of women faculty in their engineering programs. There were only two outcomes that were mapped to this path (i.e. 28.5%)

Paths with less theoretical backup, considering the relationships we proposed, are a) and b). For a) institutions that have a male leader and have not reached critical mass in 2001 will reach the outcome of doubling the proportion of women faculty by 2021. It would be important to explore which other strategies were implemented by this group of institutions that were as effective as having an ADVANCE initiative without having one since this path also covered two of the outcomes (28.5%). Similarly, those institutions that achieved the outcome through path b) would be worth exploring in terms of the strategies they implemented since they did not have an ADVANCE initiative, nor did they have a female leader. Elements that could be explored might be aligned with how much having a female leader could represent less attention to the efforts to advance gender equity because of the apparent gains represented by having a woman in a leadership position, which might be seen as another type of tokenization [39].

V. FUTURE WORK

The next stage of this project will involve the use of a larger dataset of institutions with ADVANCE initiatives. Similarly, we will soon expand to the inclusion of more causal conditions. While this particular exercise used Acker's theory of gendered organizations, other feminist theoretical approaches such as intersectionality could offer a more promising path to capitalize on the QCA method. There are some challenges in using QCA to gauge institutional change that we will be sorting out as we expand our explorations. First, the execution of QCA can take place with crisp sets (only 0/1 values), and with fuzzy sets (allowing more than two values), this exercise was limited to a crisp set, despite having some continuous variables that were later dichotomized; the next stages will explore the use of fuzzy sets and compare their efficiency to identify unique paths to the outcome. Second, we will also expand our exploration to alternative outcomes that involve the quality of faculty experiences rather than the mere presence of women faculty, such as faculty satisfaction with institutional policies. Such efforts would require a qualitative exploration of faculty at the considered institutions, which will later be translated into a quantitative dataset. QCA, as the bridge between qualitative and quantitative analyses, would be particularly suitable for such explorations.

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