Qualitative Simulation of Causal Dynamics in Higher Education using Fuzzy Cognitive Maps

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Outline

- Introduction
  - Modeling Universities as Complex Adaptive Systems
  - **Objective**: Exploratory Policy Analysis using Qualitative Simulation with Fuzzy Cognitive Maps
- Background: Computational Models of Higher Education
- Fuzzy Cognitive Map Formalism
- Qualitative Simulation of University of Activity Dynamics
- Simulation Experiments and Analysis
- Conclusions

Motivation

- As of July 2022, 73.0% of college students at all levels attend public institutions **[Education Data Initiative, 2022]**
- Policies aimed at these institutions have a significant influence on higher education
  - fiscal tensions in state funding of public higher education impact
  - the quality of education, graduation rates, and overall organizational performance of universities
- **Objective**: Presenting a qualitative causal simulation model
  - based on the Fuzzy Cognitive Map (FCM) formalism to
  - demonstrate the feasibility and utility of exploratory cause-effect analysis of resource tensions and quality in public higher education institutes

Objective

- Advocate systems approach with an exploratory modeling and analysis strategy to
  - provide a foundation to demonstrate policy analysis in the context of higher education
  - focus on a selected subset of factors with the primary objective of demonstrating the use of the computational FCM formalism to support
  - model-centric thinking.

Background

- Simulation modeling helps
  - explore the effectiveness of university operations in
  - achieving organizational outcomes while
  - providing a predictive and prescriptive tool for policy evaluation
- Types of modeling used in higher education policy analysis
  - Agent-based modeling
  - System Dynamics
- Qualitative Simulation with FCM

Agent-Based Modeling (ABM) in Education

- ABMs include autonomous agents to simulate the decisions, actions, and interactions of discrete entities.
  - study the impact of various organizational decisions on institutional performance with a specific focus on the financial perspective **[Roebber and Meadows 2012]**
  - avoiding the spread of outbreaks on campus **[Tang et al. 2022]**
  - studies of randomized testing, contact tracing, and quarantining to reveal the effectiveness of alternative strategies in protecting students, faculty, and staff **[Gressman and Peck 2020]**
  - explore industry-university links to examine the impact of collaboration structures on innovation **effectiveness [Ahrweiler, Pyka, and Gilbert 2011]**
  - social impact theory tests social communication and resource allocation on STEM yield **[Allen and Davis 2010]**
  - study scientific activity and clustering of research activity into scientific domains and disciplines **[Gilbert 1997]**

System Dynamics (SD) in Education

- Mathematical modeling approach to represent systems and their continuous non-linear behavior over time.
  - explain and predict the dynamics of complex issues and problems ranging from artificial to social and natural systems
  - taxonomy of SD models in higher education **[Kennedy 2020]**
  - implementation of sustainable development education programs is examined with a focus on the sustainability competencies of students **[Faham et al. 2017]**
  - efficient resource management and capacity planning for academic programs **[Strauss and Borenstein 2015]**

Qualitative Simulation

- Partially specified models complement numerical simulation of completely specified models.
- Qualitative and semi-quantitative models make it possible to
  - express incomplete knowledge, and
  - predict possible behaviors consistent with the available knowledge
- Monitoring, policy discovery, mechanism design, and verification can benefit from
  - the ability of a finite set of qualitative models to
  - cover the predictions of an infinite set of precise models

Qualitative Simulation

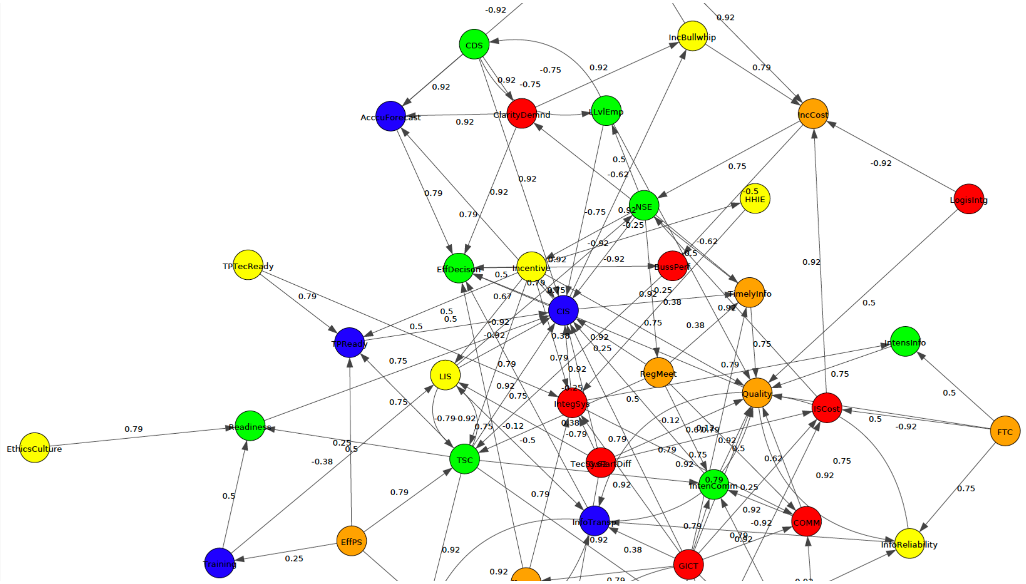
- Building a precise model needs a considerable amount of
  - qualitative reasoning about the relevant constraints to include in the model, and
  - the types of behaviors that result from the interactions among those constraints
- A computational tool for performing
  - qualitative reasoning on the way to a numerically precise model to
  - to decide which constraints to include in a model

Fuzzy Cognitive Map Formalism

- FCMs are fuzzy signed directed graphs that allow degrees of causal influence and event occurrence
  - simulate a wide range of system designs, scenarios, and decision processes
  - nonlinear dynamics permit forward-chaining inference from input causes and design options to output effects
  - can add detailed dynamics and feedback links directly to the causal model or infer them with statistical learning laws
  - can fuse or combine FCMs from multiple experts by weighting and adding the underlying fuzzy edge matrices

Fuzzy Cognitive Map Formalism

- An FCM concept node is fuzzy in general because it can take values in the unit interval [0,1] – values over time define a **fuzzy set**.
  - E.g., describes a survival threat or any other property or policy both occurs and does not occur to some degree at the same time
- consists of n concept nodes C_j and n^2 directed fuzzy causal edges e_{ij}
- concept nodes C_1 , C_2 …, C_n are nonlinear and represent variable concepts or factors in a causal system.
- A concept node's occurrence or activation value $C_i(t_k)$ measures the degree to which concept C_i occurs in the causal dynamics at time t_k.



FCM Interactive Activation Dynamics

$$C_j(t_{k+1}) = \Phi_j\left(\sum_{i=1}^{n} C_i(t_k)\, e_{ij}(t_k) + I_j(t_k)\right)$$

- The simplest threshold function is a hard threshold that produces bivalent, on-off concept node values

$$C_j(t_{k+1}) = \begin{cases} 0 & if \sum_{i=1}^{n} C_i(t_k)\, e_{ij}(t_k) + I_j(t_k) \leq 0 \\ 1 & if \sum_{i=1}^{n} C_i(t_k)\, e_{ij}(t_k) + I_j(t_k) > 0 \end{cases}$$

- For systems that involve continuous dynamics, a monotonic increasing nonlinear function can be used.
- Logistic causal activation functions have sigmoidal structure that approximate the hard threshold function, if the shape parameter c > 0 is large enough

$$C_j(t_{k+1}) = \frac{1}{1 + exp(-c\sum_{i=1}^{n} C_i(t_k)\, e_{ij}(t_k) - cI_j(t_k))}$$

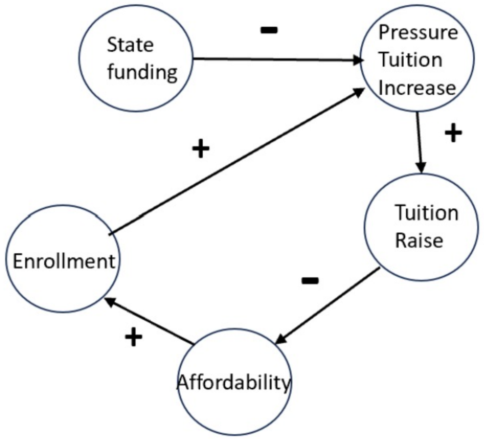
Comparison with Other Models

- Two other approaches to modeling causal worlds are
  - system-dynamics (SD) models and
  - Bayesian belief networks (BBNs)
- SD models represent and simulate causal interactions
  - But SD models have static parameters. Domain experts choose the parameters of the subsystems and their interconnections.
  - FCMs admit both data-driven and expert-driven adaptation of the model structure and the model parameters. Statistical learning algorithms estimate causal edges from training data. Experts can also state edge values directly.
- SD models often account for stochasticity by using sensitivity analyses at the end of modeling.
  - FCMs build uncertainty into their very structure.

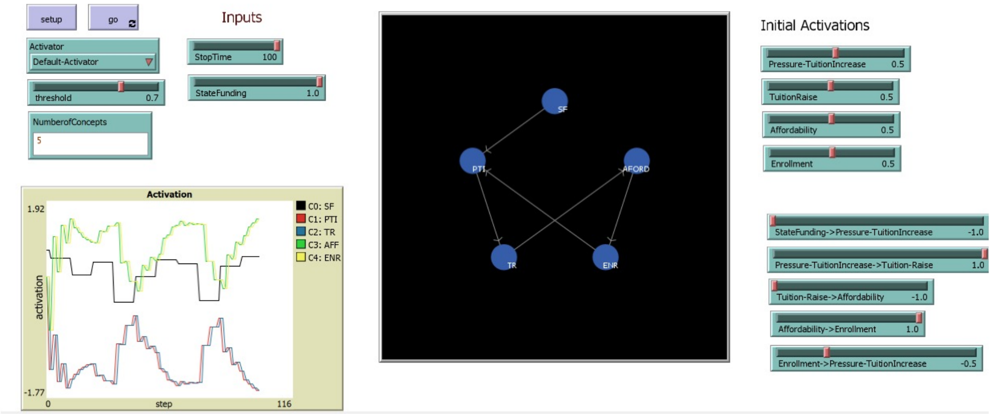
Comparison with Other Models

- BBNs model uncertain causal worlds with conditional probabilities.
  - requires a known joint probability distribution over all the nodes of the directed graph
  - may not be practical for large numbers of nodes.
- Forward inference on a BBN tends to be computationally intensive
- The directed graph is usually an acyclic graph – has no closed loops.
  - The acyclic structure simplifies the probability structure
  - but ignores feedback among the causal units

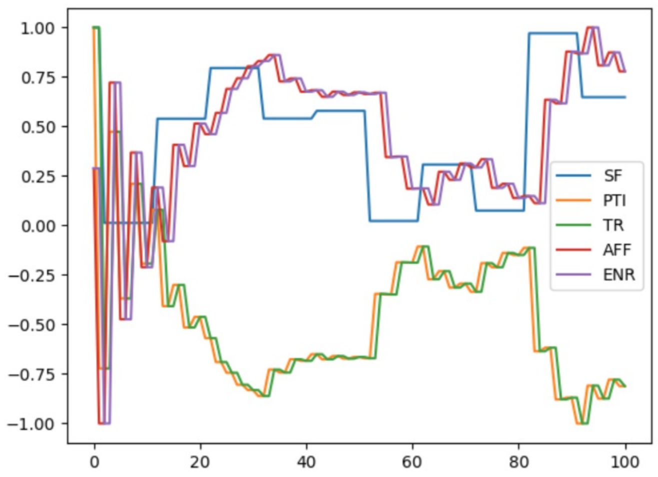
Qualitative Simulation of the University Activity Dynamics



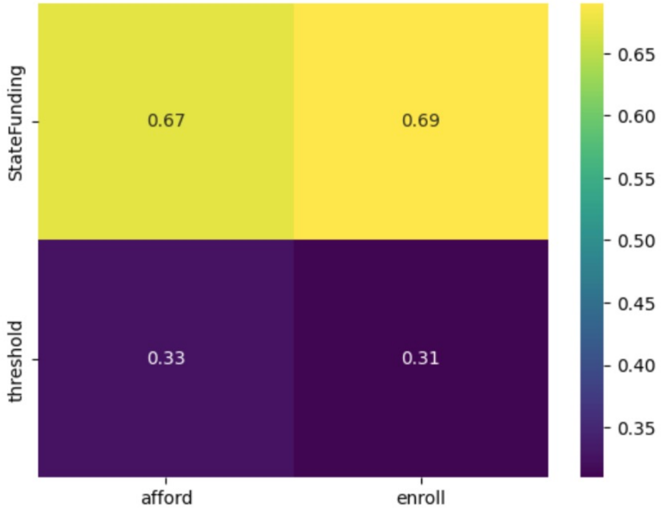
(a) FCM Concepts and Dependencies



(b) Netlogo Implementation of the FCM Model

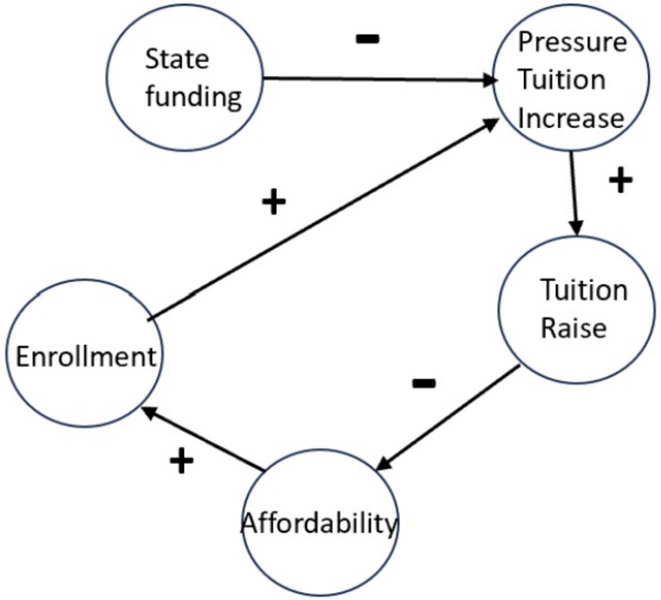


(c) Normalized Activation Levels

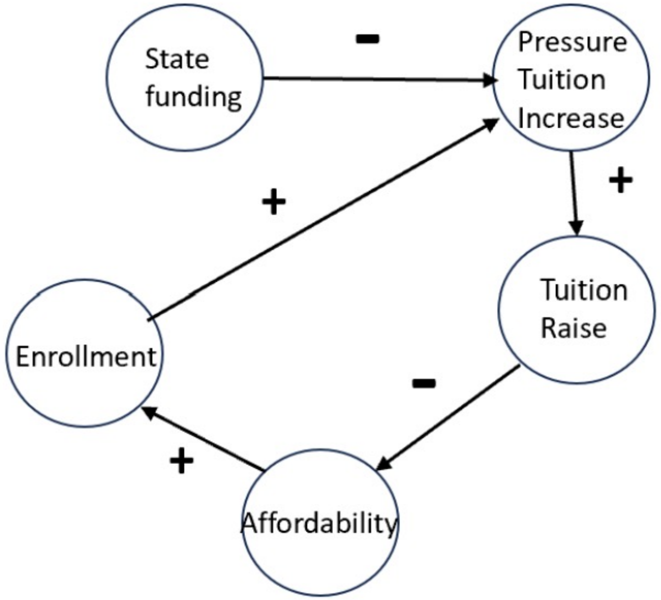


(d) Feature Scoring

- State funding is input concept that is varied to assess the impact of fiscal tensions on the affordability and enrollment levels.
- According to **[Kim and Ko 2015]**, decrease in state funding levels increases **pressure for tuition increase**, which then results in an increased likelihood of **tuition increase**.
- impact of **tuition increases** on the **affordability** of higher education is well documented **[Hemelt and Marcotte 2011]**

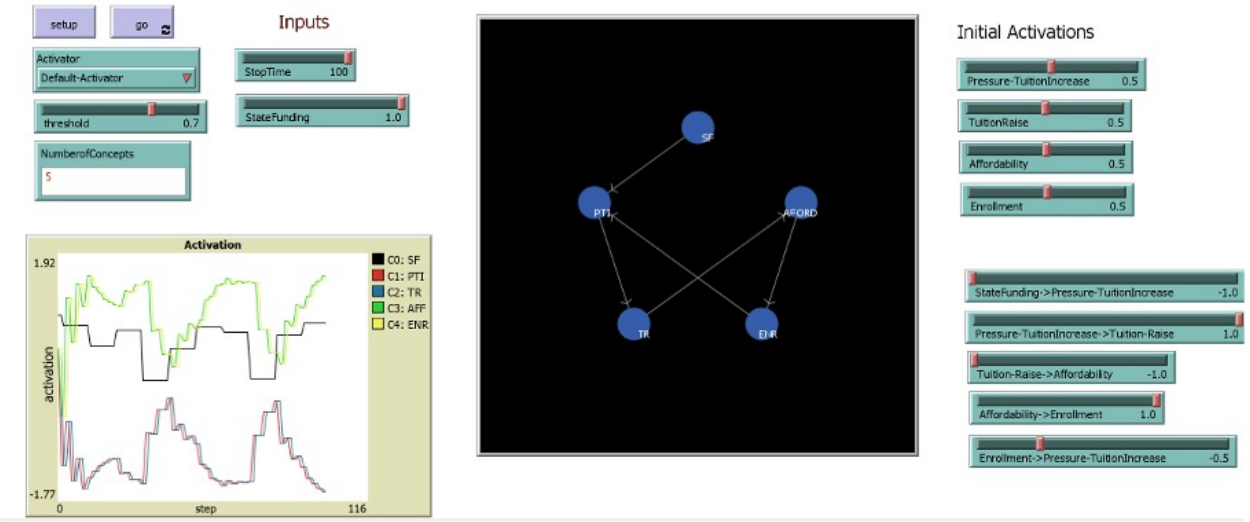


- according to **[Heller 1999]** decreasing affordability reduces enrollment levels
- In relation to the dependency between **enrollment** levels and **pressure for tuition increase**, we consider the empirical results that suggest diseconomies of scale for large universities **[Brinkman and Leslie 1986]**



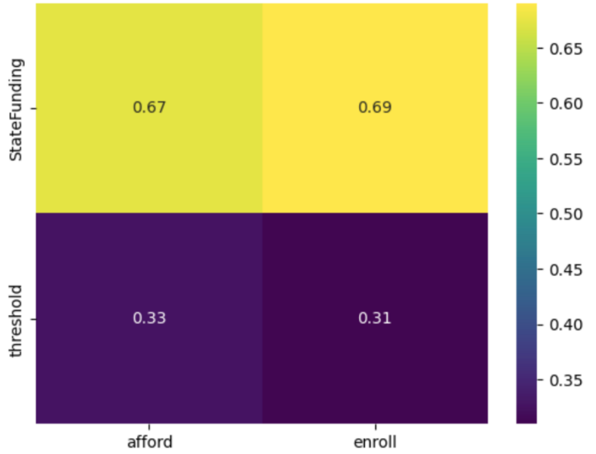
NetLogo Implementation

- Baseline conceptual model is implemented within the NetLogo environment
- The Netlogo model is available at *github.com/yilmale/University*

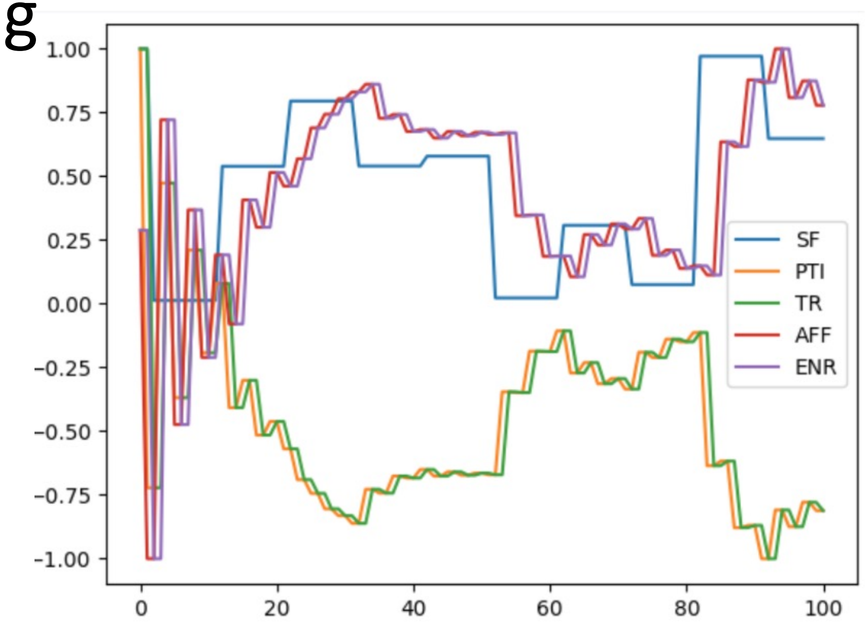


Feature Scoring

- Feature scoring reveals the significance of the **state funding** variable on affordability and enrollment levels.

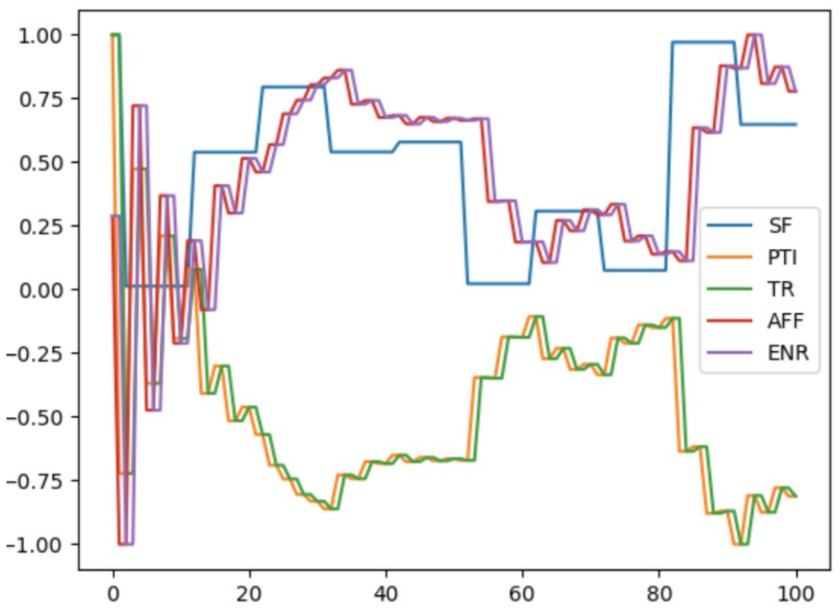


The minimal baseline model facilitates instilling confidence in implementing the interactive activation dynamics process underlying the FCM formalism.



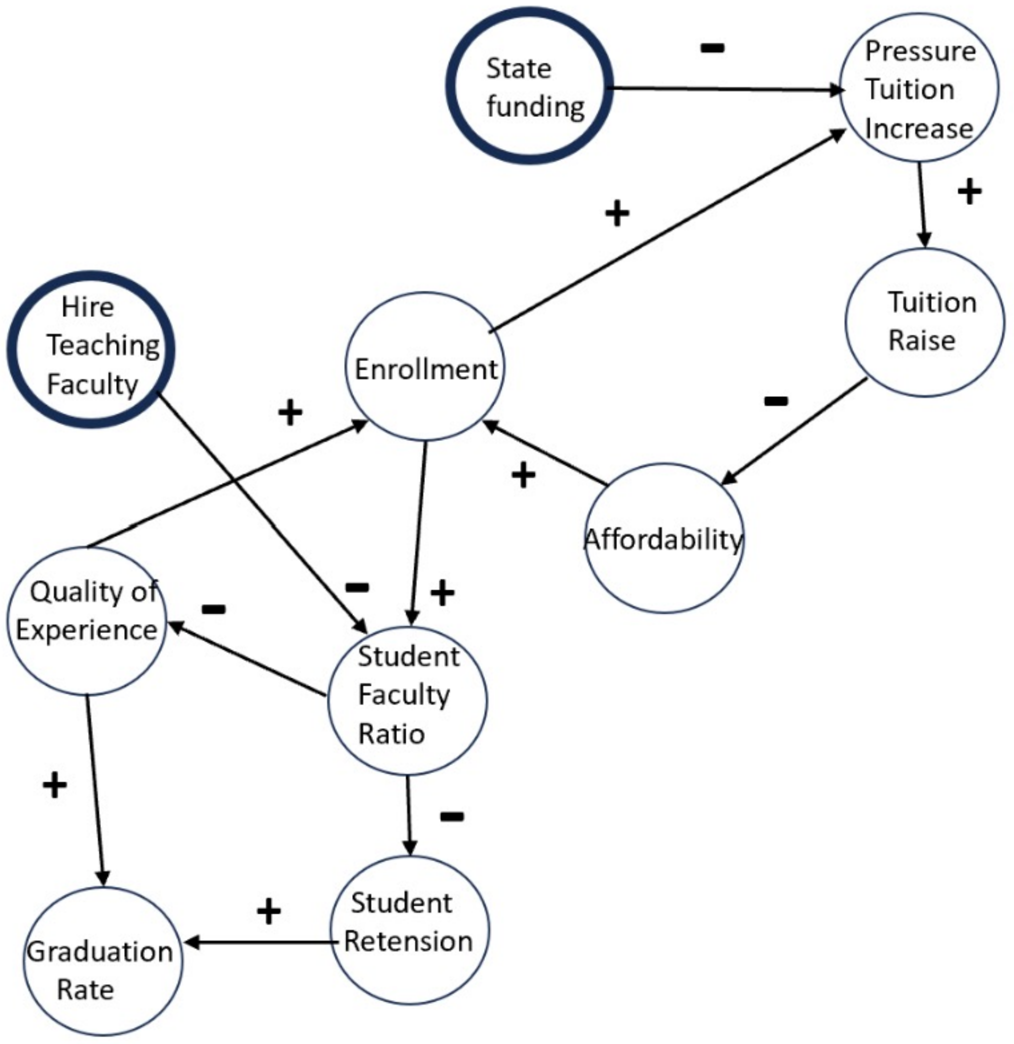
Trend Analysis – Face Validity

- increase (decrease) in affordability and enrollment follows with a slight lag the increase (decrease) in the state funding level.
- Similarly, the change in the activation of pressure for tuition raise and the tuition rate follows the change in the state funding activation in the expected direction.



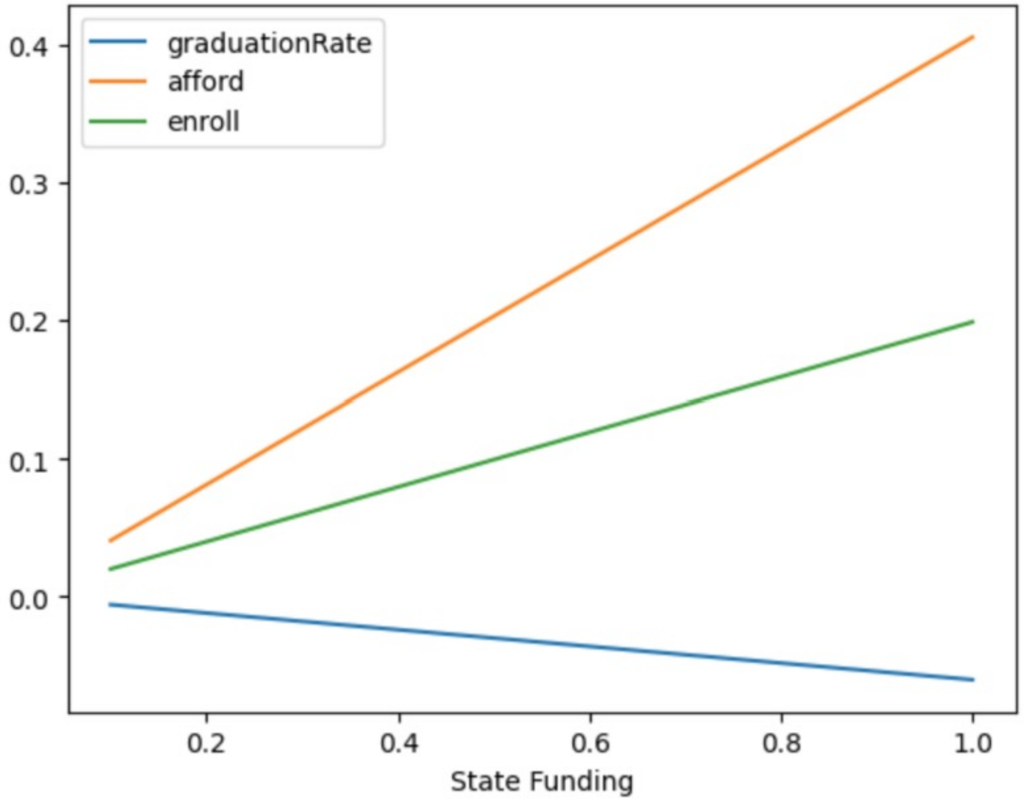
Extended FCM Model

- Additional concepts representing the **student-faculty ratio**, **student retention**, **graduation rate**, and **quality of experience**
- An increase in enrollment levels results in an increase in student-faculty ratio, negatively influencing student retention.
- Lower levels of student retention reduce graduation rates.
- Higher levels of student-faculty ratio adversely affect experience quality, which is an important criterion for increasing graduation rates.



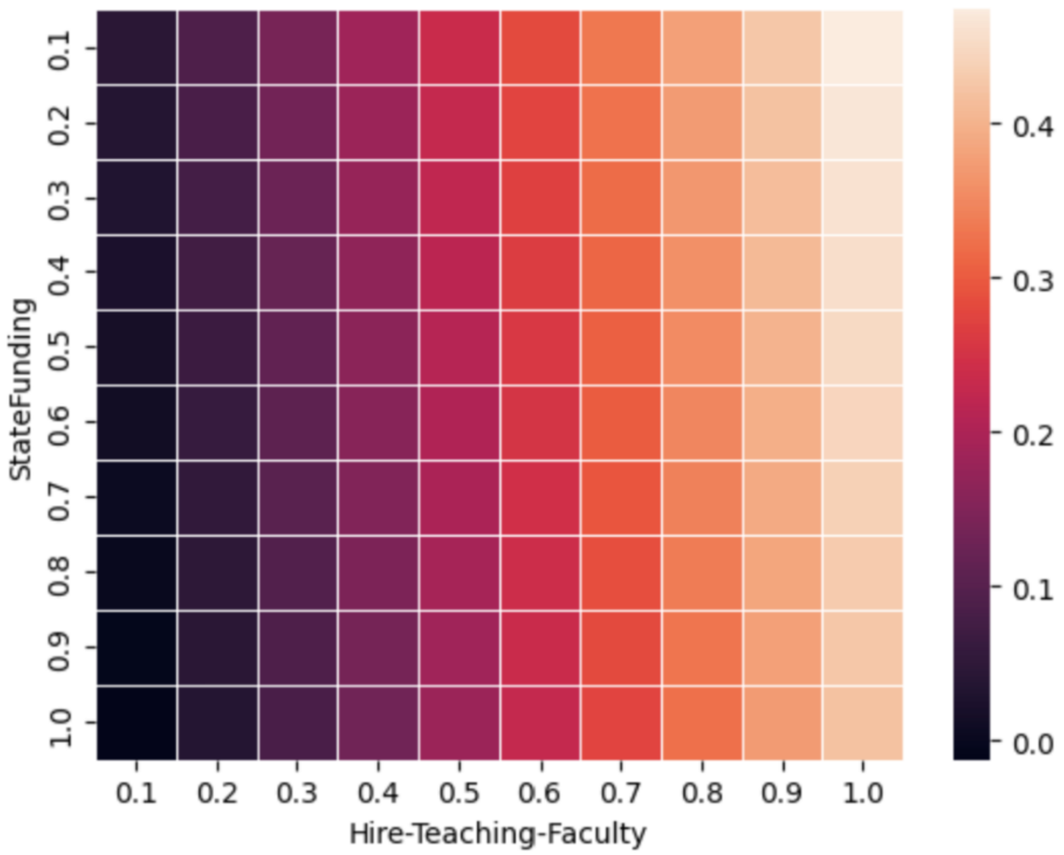
Simulation of the Extended FCM Model

- graduation rates decline regardless of state funding activity in the absence of teaching faculty hiring activity.
- State funding does not produce sufficient graduation activity at lower teaching support levels, assuming that state funding does not contribute to reducing the student-faculty ratio through other mechanisms.



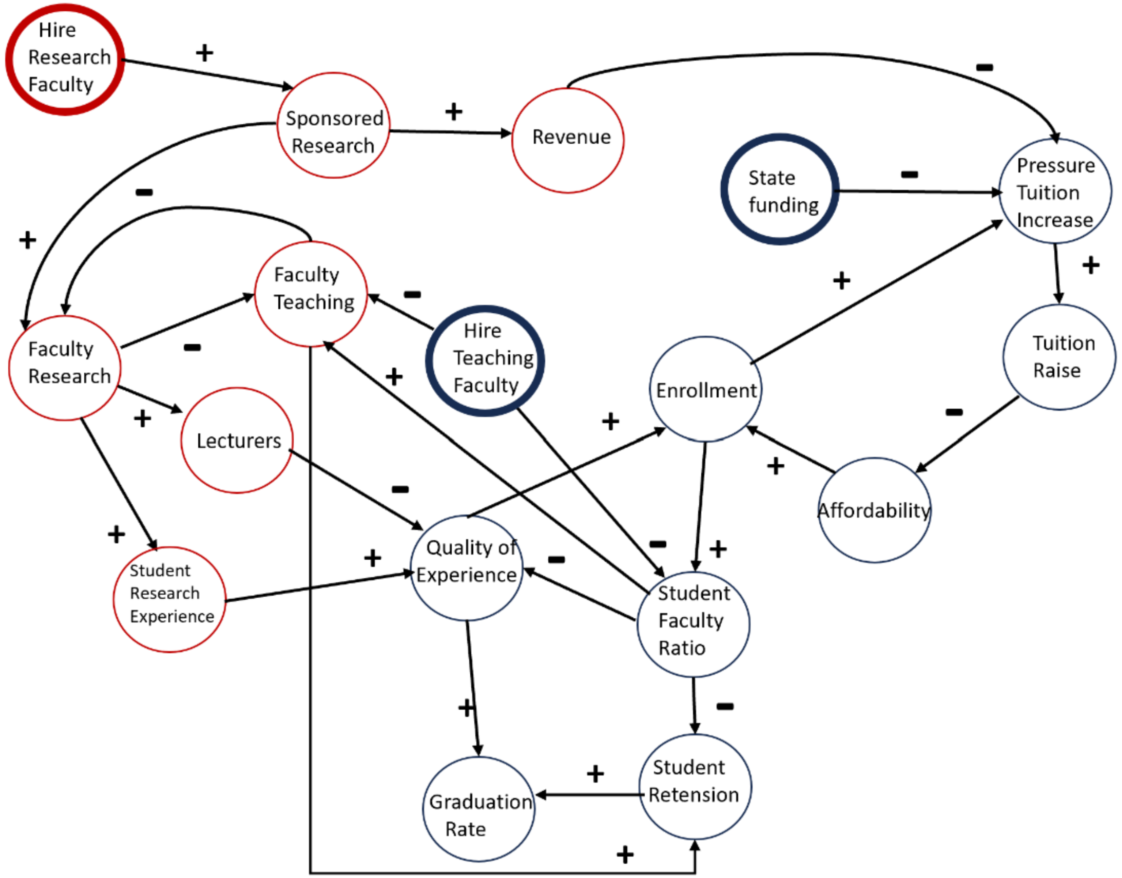
Simulation of the Extended FCM Model

- The factorial experiment examining the interaction between state funding and hiring teaching faculty shows that hiring teaching faculty is critical to increasing graduation rate activity.



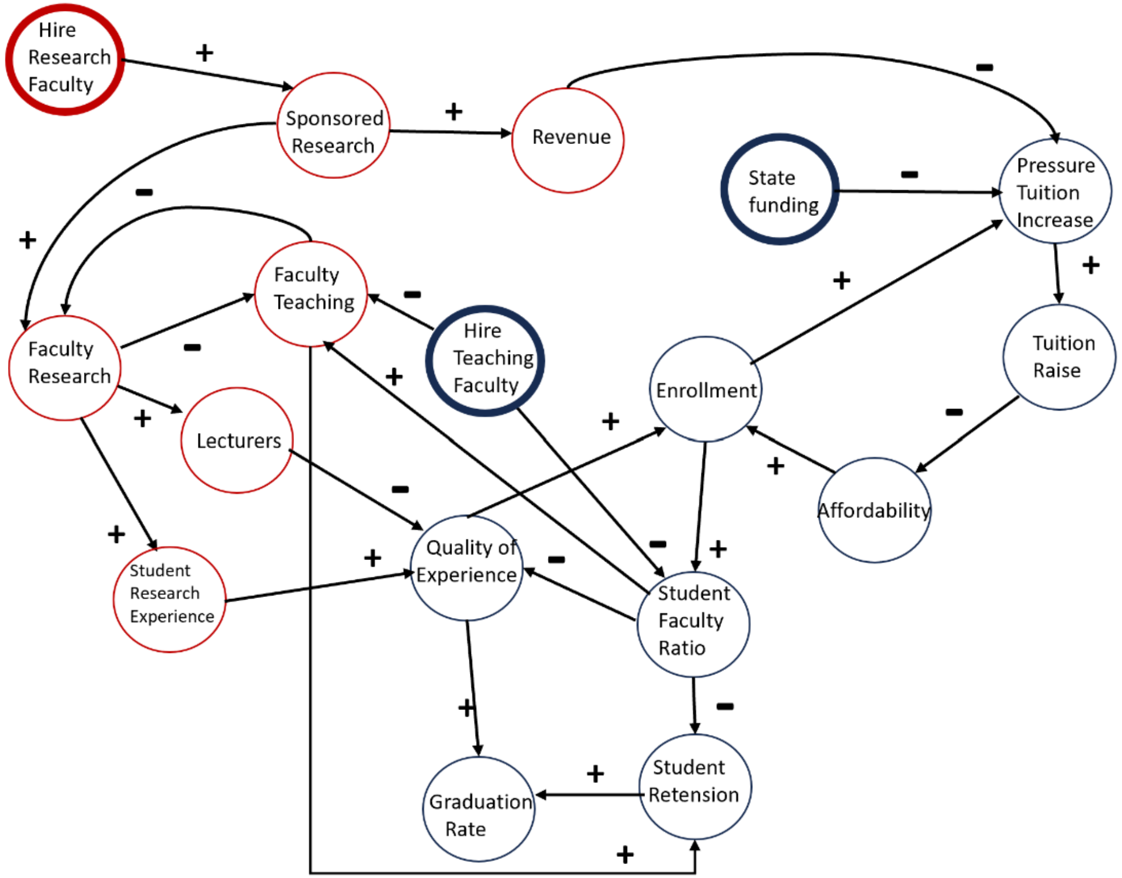
Including the Research Component

- **Hiring-Research-Faculty** is considered as an input concept that can be controlled by the university administration.
- By **hiring research faculty**, the university can be expected to <u>increase</u> the level of **Sponsored Research**, which generates new **Revenue**.



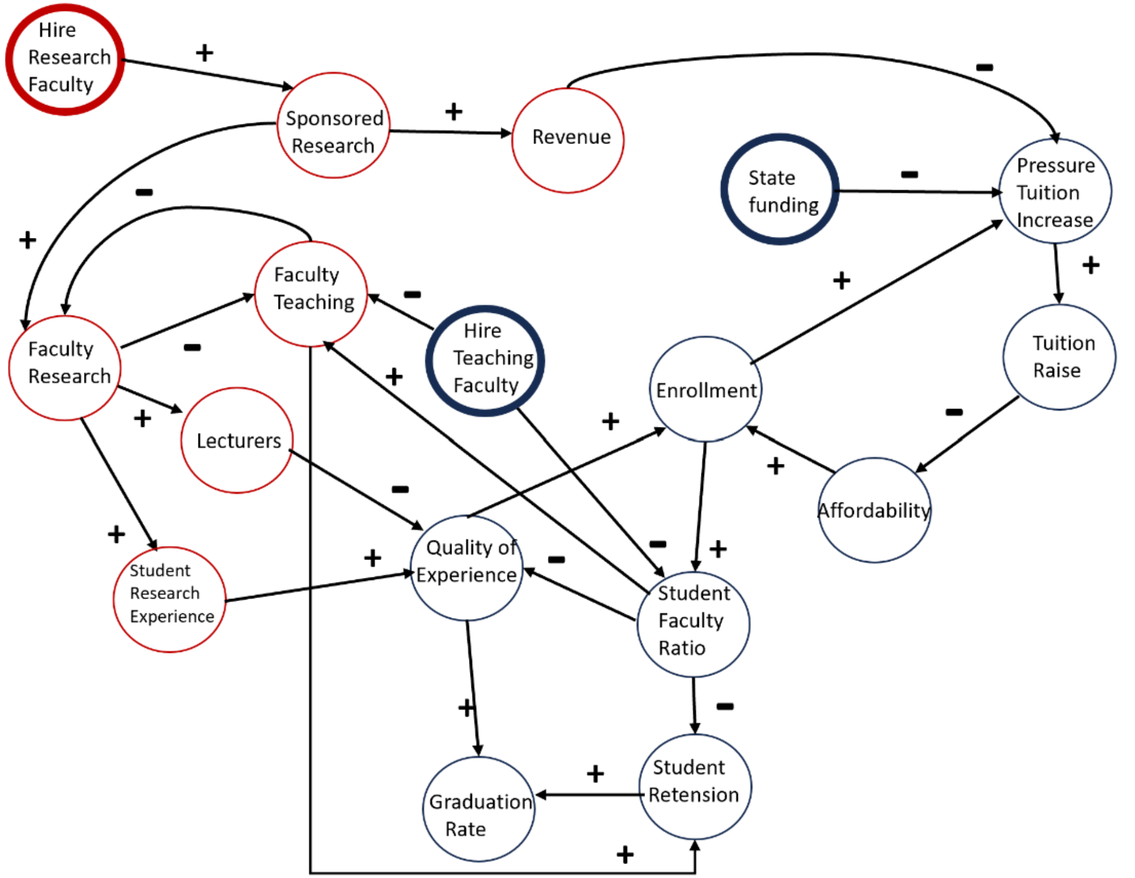
Including the Research Component

- **Sponsored research** is expected to <u>increase</u> the **research activity** by faculty specified by the Faculty-Research node in the FCM.
- However, **more faculty research** results in **lower levels of teaching activity** due to administrative policies such as course buyouts or assigning teaching responsibilities to graduate students or lecturers.



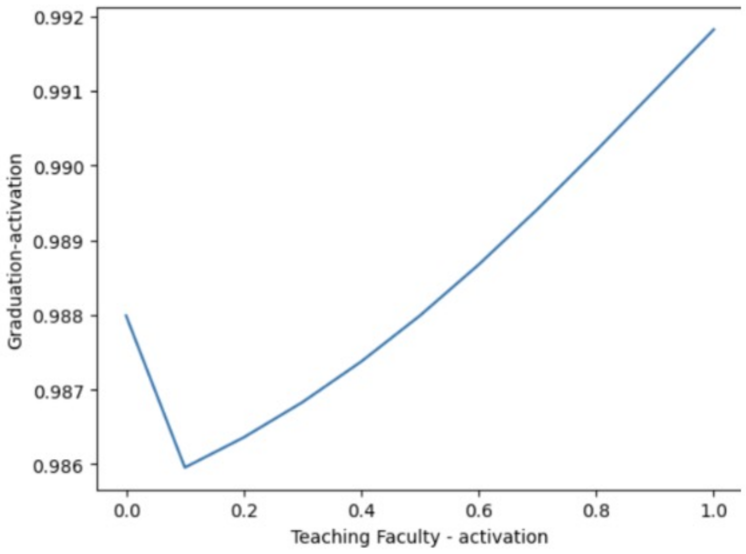
Including the Research Component

- **Delegation of teaching to lecturers** reduces the **quality of experience** for students, resulting in an adverse impact on **graduation** and **student retention**.
- On the other hand, with **increased faculty research activity,** students have more opportunities to be involved in research, and such research experience contributes to an increased **quality of experience**.



Analysis of the Extended Model

Increasing the teaching resource capacity beyond the inflection point consistently improves the graduation rate performance.

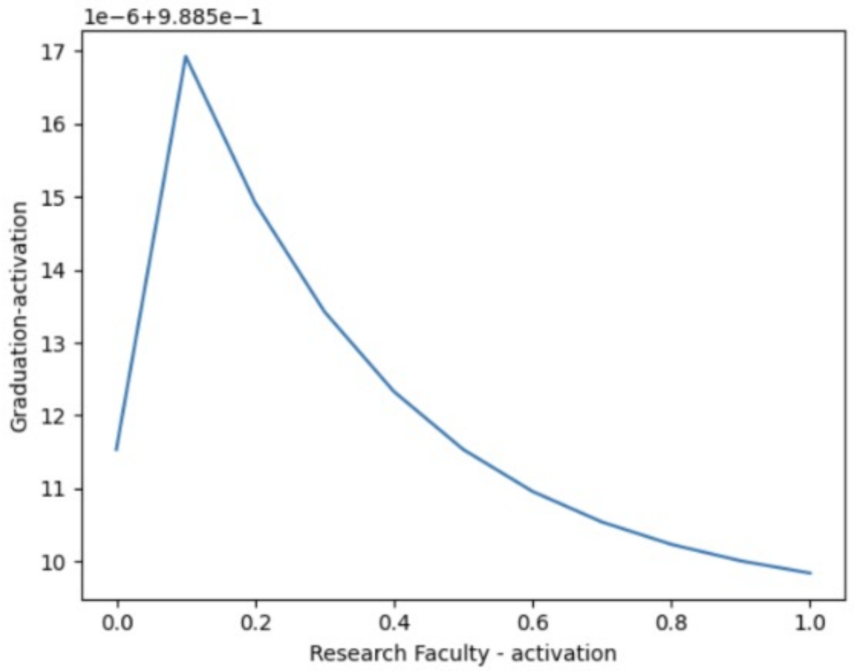


(a) The Impact of Teaching Capacity on Graduation Rate

Analysis of the Extended Model

An increase in the research capacity improves the graduation rate through moderate levels of increase in student research experience that positively affects overall student experience.

Increasing the research load over the inflection point decreases the overall student experience and graduation rate due to its impact on suppressing teaching capacity.



(b) The Impact of Research Capacity on Graduation Rate

ANOVA Analysis of Quality of Experience

Supports the Feature Scoring analysis by highlighting the significance of state funding and teaching capacity.

Two-way interactions between the factors reveal that the impact of individual factors is not dependent on other factors.

q: Quality of Experience, **S:** State Funding, **T:** Teaching Faculty, **R:** Research Faculty

Dep. Variable:	q	R-squared:	0.815
Model:	OLS	Adj. R-squared:	0.814
Method:	Least Squares	F-statistic:	970.7
		Prob (F-statistic):	0.00
		Log-Likelihood:	2956.4
No. Observations:	1331	AIC:	-5899.
Df Residuals:	1324	BIC:	-5862.
Df Model:	6		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
Intercept	0.2839	0.004	75.393	0.000	0.277	0.291
S	0.0055	0.006	0.987	0.324	-0.005	0.016
T	0.1728	0.006	30.922	0.000	0.162	0.184
R	-0.0001	0.006	-0.027	0.979	-0.011	0.011
T:R	-6.101e-05	0.007	-0.008	0.993	-0.014	0.014
S:R	1.571e-05	0.007	0.002	0.998	-0.014	0.014
S:T	0.0024	0.007	0.335	0.737	-0.012	0.017

Omnibus:	304.477	Durbin-Watson:	0.093
Prob(Omnibus):	0.000	Jarque-Bera (JB):	543.789
Skew:	1.463	Prob(JB):	8.27e-119
Kurtosis:	4.116	Cond. No.	21.5

Conclusions

- Analyzing policies in the higher education system requires
  - understanding nonlinear dependencies between factors, including
  - positive and negative feedback loops that can lead to nontrivial outcomes.
- For such complex systems, the tools and models of complexity can offer reliable frameworks to gain insight into the causal dynamics of constituent elements.

Conclusions

- Demonstrated a semi-qualitative model based on the Fuzzy Cognitive Map formalism
- Conducted experiments to examine the tension among state funding, research capacity, and teaching capacity in relation to the quality of student experience and graduation rates.
- The causal dependencies presented in the model are based on theoretical and empirical findings reported in the extant literature.
- The results indicate the significance of teaching capacity on graduation rates, while state funding affects the affordability of higher education.