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DIGITAL TRANSFORMATION STRATEGY DYNAMIC FOR UTILITY SMART GRIDS: SYSTEM DYNAMICS MODELLING IN UNTANGLING COMPLEXITY

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Abstract

This paper explores System Dynamics Modeling (SDM) as a tool for addressing the complexities of large-scale systems, focusing on the digital transformation (DT) of the electricity utility industry and the rise of smart grids. While DT is widely recognized for its strategic significance, current research lacks methodologies to help business strategists manage its complexity over time. This paper fills that gap by demonstrating how SDM offers a structured approach to strategy design and long-term planning. Smart grids, driven by technological innovation and shifting consumer needs, pose significant challenges for policymakers and utility managers. Their interconnected nature, characterized by feedback loops, creates a socio-technical system that requires careful management. However, SDM provides a beacon of hope, helping stakeholders navigate this complexity by allowing them to simulate system behaviors, test interventions, and design strategies to address key issues such as grid stability, energy management, and consumer engagement. This research introduces a system dynamics model for utility smart grids, breaking the system into twelve submodels. This decomposition method not only makes large-scale systems more manageable but also fosters a collaborative modeling approach. By simulating policy interventions, stakeholders gain critical insights to support informed decision-making in innovative grid development. This approach emphasizes the shared responsibility in managing large-scale systems, promoting a collaborative and inclusive process. The study highlights that SDM and decomposition techniques are both academic and practical tools for improving complex systems' strategic planning and policy design. The paper concludes by identifying future research opportunities in strategic modeling using SDM, particularly in longitudinal studies in utilities.

***Key words**: digital transformation, longitudinal research, dynamic modeling, feedback loops, system dynamics, smart grids, grid stability,*

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energy management, customer engagement, large-scale systems, decomposition techniques, policy design.

1. Introduction

Digital transformation (DT) is essential for modern businesses, driven by technological progress and evolving consumer behaviors. However, many organizations face difficulties executing effective DT strategies due to the complexity and absence of practical methodologies. Despite the significance of DT governance, there is a notable lack of longitudinal studies that model the long-term dynamics of DT, which complicates future planning. System Dynamics Modeling (SDM) is proposed as a valuable tool for addressing these challenges, particularly in large-scale systems like the transition to smart grids in the electricity sector. Smart grids pose unique challenges—such as grid stability and energy optimization—and SDM aids in simulating policy interventions, understanding feedback loops, and supporting strategic planning.

We propose a decomposition approach to building a system dynamics model tailored to utility smart grids, improving understanding by breaking down the system systematically. This method, as introduced by Chiriac et al. (2011), divides complex systems into major components and then into smaller parts, enabling comprehensive strategy development (Ledet and Himmelblau, 1970). Our approach identifies twelve submodels to capture the smart grid's complexity. The paper further details the construction of a Causal Loop Diagram (CLD), a key element in developing a robust system dynamics model (Binder et al., 2004).

2. Literature Review

Research indicates that nearly 30 percent of digital transformation efforts fail, even among Fortune 500 firms (Siebel, 2017). This failure is often due to managers not recognizing that DT requires a holistic strategy involving the organization's internal and external environments, including employees, resources, customers, suppliers, regulators, and the government. Digital transformation (DT) signifies organizational change influenced by widespread digital technology diffusion, encompassing broader organizational change. Insights from scholars suggest organizational designs must adjust dynamically to their environments, introducing the idea of a "malleable firm" (Hanelt et al., 2021). However, DT processes result from converging organizational, technological, and environmental forces within digital business ecosystems ((Bharadwaj et al., 2013)). Systems theory emphasizes that DT involves organizational design and interactions with customers, regulators, and platforms. Systems theory and system dynamics highlight that changes in one area can impact the entire system ((Fowler, 2003)). Key feedback loops in DT include the interaction between technology organizations and society, addressing significant social and ethical issues that can drive the creation of responsible technologies (Kutzschenbach, 2017). DT involves complex technological, organizational, and cultural changes, understood through system theory and system dynamics. Scholars can use these frameworks to study DT's dynamic changes within organizations and industries. Smart meters symbolize DT by providing real-time energy consumption insights, empowering consumers, and enhancing grid management through data analytics and AI. (Alotaibi et al., 2020). Regulatory frameworks have supported digital transformation initiatives in the electricity sector, promoting renewable energy adoption and emissions reduction. The sector's transformation showcases its adaptability and innovation. Future trends will focus on energy storage, electric vehicles, and microgrid technologies. (Matallana et al., 2019). The transition towards smart grids involves fundamental changes in the electricity industry's operating model, integrating technologies for more efficient energy allocation. (Pereira et al., 2018) and aiming for sustainability and energy efficiency (Świątowiec-Szczepańska and Stępień, 2022), adapting to market dynamics, technological innovations, and regulatory requirements to enhance operational efficiency and meet evolving consumer needs (Gebauer et al., 2014).

3. Decomposition of Large-Scale System

As stated earlier, our Smart Grid model will consist of twelve subsystems, as shown in Table 1.

Table 1: Twelve sub-systems of the Smart Grid System in a Utility

1. Energy Efficiency (EE) and Peak Demand Management Model: 2. Stability vs Sustainability sub-model (Described in this paper as Microgrid DER Model 3. Market Dynamics Sub-Model: Examines supply, demand, and competition. (Comprises of Stocks: Energy Demand, Energy Supply, Market Prices Flows: Energy Production, Consumption, Price Adjustments Rates: Demand Growth Rate, Supply Growth Rate, Price Change Rate Feedback Loops: Positive between Demand and Price; Negative between Price and Consumption)	4. Regulatory and Policy Sub-Model: Considers regulatory environment and policies 5. Cybersecurity Sub-Model: 6. Renewable Energy Integration and Sustainability Sub-Model: 7. Digital Resources Sub-Model: 8. Utility, Customer, and Societal Benefit Model: 9. Energy Conservation 10. Modelling Customer Response to Smart Grids (Described in this paper as customer response to HEQ submodel) 11. Modeling Cost Benefits Analysis and Investment Returns: 12. Infrastructure Development Sub-Model: Focuses on developing transmission lines and substations.

3.1 Modeling A Microgrid using System Dynamics Modelling

Considering limitations in space and time, in this paper, we have showcased the development of a causal loop diagram (CLD) for a specific subsystem, the Micro Grid, in conjunction with Customer Engagement in a Utility employing Vensim. We have illustrated the process of visually defining stocks, flows, feedback loops, and delays, showcasing their interconnectedness to depict the system's dynamics. In the following sections, we describe the remaining sub-models and list the variables, stocks, flows, feedback loops, delays, etc. This will aid utility executives in relating to their work. A microgrid is a network of interconnected loads and distributed energy resources (DER) that function as a single controllable entity relative to the primary grid. It can operate in grid-connected and island modes, thus enhancing customer reliability and resilience to grid disturbances. Due to their intermittent generation patterns, the increasing integration of distributed renewable energy and storage represents a challenge. Microgrids face stability, power electronics, safety, communication, and energy management challenges, underscoring the need for robust control and Energy Management System (EMS) strategies to handle fluctuations. A system dynamics model can help understand the complex interactions within a microgrid affected by DER integration. This model encompasses various stocks, flows, and rates that govern these interactions, including delays that represent the system's response time to changes in DER penetration and generation/consumption dynamics. To effectively model DER penetration impacts using system dynamics, it is necessary to identify stocks and flows, pinpoint feedback loops, as detailed below in Table 2. and build causal loop diagrams (CLD) to incorporate these elements. This will offer insights into the microgrid's operation under varying conditions.

Table 2. Stocks, Flows, Rates, Delays, Feedback Loops or Dynamic Modelling

1. Stocks and Variables	2. Micro Grid DER Model: Flows and Rates
Stability Index	*Power Generated by Distributed Resources*
System Inertia	*Power Consumed by End Users*
System Stability	*Power Flow to/from the Grid*
Intermittency factor	*Energy Storage*
Renewable Generation Capacity	*Coal Generation Capacity Addition rates*
Hydrogen capacity	*Nuclear Power Addition Rates*
Nuclear Capacity	*Hydro Addition rates*
Coal Capacity	*RES Addition rates*
Sustainability Index	*Smart Meter Addition rate*
Battery Storage Capacity	*Economic Activity Rate (GDP)*
Gas Generation Capacity	*Demand Growth Rate*
CO2 Emission	*High-efficiency equipment purchasing rate*
High-Efficiency Equipment	*Customer Engagement Rate*
Population	*Rate of Change of Stability Index*
High Efficiency Equipment	*Rate of Change of Population*
Availability	5. Micro Grid DER Model: Stochastic Process
High Efficiency Equipment Price	*Intermittencies:*

Smart Meter Population *Customer Intervention* *Customer Utility Co-Creation Index* *Demand Side Management Index* *Proportion of Dynamic Tariff Population* *Economic Activity* *Customer Demand* 3. Microgrid DER Model Units for Stocks and Variables: *Energy Storage Capacity: Megawatt-hours (MWh)* *Stability Index of the Microgrid: Unitless* *Safety and Protection Index: Unitless* *Energy Management System Performance: Unitless* 4. Microgrid DER Model Units (Rates and Delays) *DER Penetration Rate: Percentage per period (%/year)* *Power Fluctuations Rate: Kilowatts per period (kW/year)* *Power Generation: Kilowatts per period (kW/year)* *Consumption Rate: Kilowatts per period (kW/year)* *Stability Index Factor Unitless* *Delays: Response Time to Power Fluctuations:* *Time (minutes, hours)*	*Intermittencies associated with DERs can be represented as a stochastic process that affects the power generation flow. For example, you can model the probability distribution of power generation levels from DERs over time based on historical data or predictive algorithms. Incorporate this intermittency factor using stochastic methods into the power generated by distributed resource flow. This will affect the overall power balance in the* 6. Micro Grid DER Model: Feed Back Loops *Positive Feedback Loop: Increased penetration of DERs leads to lower system Inertia, which degrades the stability index. This prompts more investments in stability measures like storage batteries and grid enhancement, further increasing the stability index.* *Negative Feedback Loop: Fluctuations in power generation from DERs during weather-induced intermittencies trigger actions from the energy management system to balance supply and demand for stabilizing the microgrid and increasing reliance on external grid support from fossil fuels, reducing sustainability index.* 7. Micro Grid DER Model: Mitigation Strategies: We are implementing advanced energy storage systems to buffer fluctuations in power generation. We are enhancing power electronic interfaces to improve efficiency and accommodate variable generation from DERs. We are strengthening safety and protection systems to ensure grid stability and prevent equipment damage. We are improving communication systems for real-time monitoring and control of distributed resources. We optimize energy management algorithms to effectively balance supply and demand in response to intermittencies. We are Enhancing the grid infrastructure. Moreover, it added more nuclear capacity.

5. Results

The decomposition of large-scale systems in conjunction with system dynamics modeling is a valuable tool for strategic design in digital transformation.

Decomposition techniques play a vital role in addressing the intricacies of large-scale systems. Decomposition simplifies the overall synthesis and design process by breaking it down into smaller, more manageable sub-problems and eases the challenge of integrating subsystems. One of the core issues in complex systems integration arises from the involvement of multidisciplinary teams, each operating with different expertise and often using incompatible tools. Decomposition techniques facilitate cross-disciplinary collaboration, enabling the seamless integration of various subsystems while allowing teams to focus on their specific areas without losing sight of the larger system goals. Organizing the system into smaller, focused parts makes it easier to manage complexities and achieve a cohesive design for innovative smart grid solutions.

Next, we illustrate how a causal loop diagram (CLD) for the microgrid is developed using Vensim to study the impact of distributed energy resource growth on the stability of the grid supply.

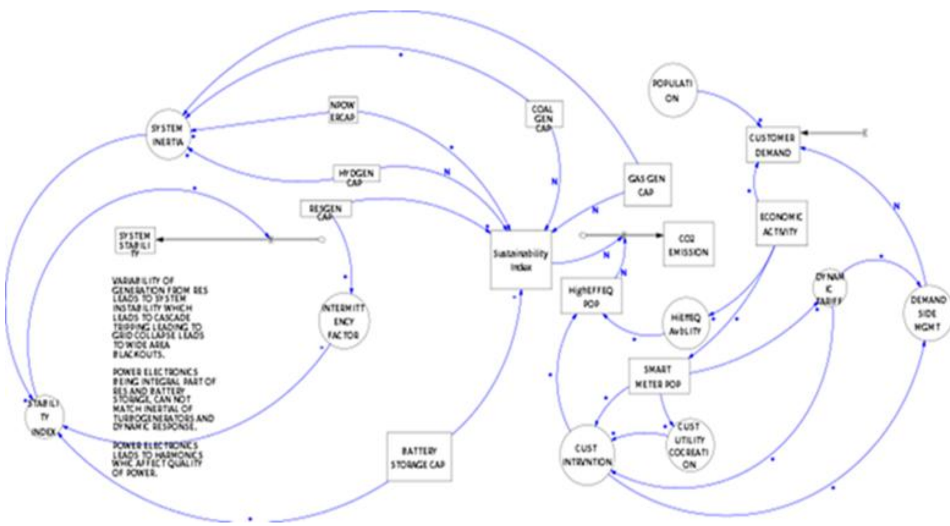

Figure 1: Causal Loop Diagram, the first step in developing a system dynamic model

The Goal of the Smart Grid Strategy is accentuated in a pilot-scale Micro-Grid Model, whose CLD is shown in Figure 1.

The model's goal is to meet a targeted 'Sustainability Index' defined by Climate Change Goals, keeping in view a desired 'Stability Index' for the power supply determined by the Regulator to assure customers of a reliable Power Supply.

From the preliminary analysis and study of the CLD, the positive and negative loops in a power grid and any growth of renewable energy sources comprising mainly static equipment reduce system inertia. In contrast, fossil-powered power generation, mainly comprised of sizeable rotating equipment, positively contributes to system inertia, providing a reserve in case of any disturbances when a generating system goes out of action. Hence, to maintain balance, we will need a stabilizing loop. Thus, while renewable energy sources like wind and solar are considered "unlimited" in the long term, there is a technical limit to how much renewable energy can be integrated into a grid before impacting stability due to their intermittent nature. This requires additional grid infrastructure and energy storage solutions to manage fluctuations in supply and maintain a balanced grid. Besides, since the smart grid is bidirectional, a safety and protection loop must be juxtaposed with the stability loop.

The customer behavior loop shows that the availability of HEQ (High-Efficiency Equipment) has positive feedback on customers' Purchases of HEQs, thus increasing the population of HEQs, which has positive feedback on the sustainability index. Customer Demand is influenced by both the population and the economic activity index. However, the utilities lack customer-friendly applications that help them reduce their bills or improve their safety applications with intelligent meters, resulting in a decaying loop and a loss of customer motivation.

6. Proposed Future Course of Research

This study is a broad exploratory study that shows the use of decomposition techniques in analyzing large complex systems using system dynamics modeling and feedback loops. The author is working on the development of the complete system dynamics model as a part of future research, and the steps that must follow are as follows,

- Develop the Stock and Flow Diagram
- Parameter Estimation
- Develop the validation against real-world data.
- Use simulation to assess policy effectiveness.

This sequence of steps must be followed for the 12 subsystems defined by earlier decomposition analysis and a unified system dynamics model developed.

Future research must focus on developing indices like the stability or sustainability indices, which involve defining objectives, selecting indicators, fixing metrics, weighing them, collecting data, normalizing data, aggregating scores, benchmarking, validating, communicating, and improving the index.

7. Conclusions

By following this outline defined in the paper using the decomposition technique for large-scale systems and system dynamics modeling, future researchers can develop a robust System Dynamics model that enhances understanding of digital transformation strategies in utilities and captures the intricate feedback loops and time-dependent behaviors inherent in these systems. System Dynamics modeling allows for the simulation of various strategic interventions over extended periods, providing invaluable insights into the long-term impacts and potential unintended consequences of different policies. This dynamic approach enables utilities to test and refine their strategies iteratively, ensuring more resilient and adaptive decision-making frameworks grounded in comprehensive, data-driven analysis.

Dynamic modeling is particularly significant for longitudinal studies of smart meter and smart grid strategies, as it enables a deeper understanding of the time-based processes that shape adoption and development across regions. Our research applies system dynamics modeling to explore why countries like Italy and Finland have outperformed others like Germany in embracing smart meters and grids. Italy, for example, achieved a 94% smart meter penetration rate by 2018, while Finland reached full deployment by 2014. In contrast, Germany has lagged, with only about 15% penetration by 2021, illustrating the complexity of strategic decision-making and its outcomes. The significance of our work lies in uncovering the dynamic factors behind these performance differences. My research leverages system dynamics to develop behavioral theories that explain the evolution of smart grid strategies by focusing on the managerial decisions that influence technology adoption over time. System dynamics is uniquely positioned to address gaps where traditional strategic approaches have struggled, particularly in understanding feedback loops, delays, and tipping points that drive long-term change. Our contribution adds a dynamic dimension to strategy research, helping to provide more effective tools for utilities and policymakers to navigate the complexities of smart grid transformation." Ultimately, System Dynamics becomes a powerful tool for shaping sustainable, efficient, and customer-centric utility transformations.

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