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ORIGINAL

Exploring Approaches to Low Fertility through Integrated Application of Big Data-based Topic Modeling and System Dynamics: The Case of South Korea

Explorando enfoques para la baja fertilidad a través de la aplicación integrada del modelado temático basado en Big Data y la dinámica de sistemas: El caso de Corea del Sur

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ABSTRACT

This study examines the multidimensional aspects of low fertility by integrating big data text mining with system dynamics analysis. While previous research primarily utilized macroeconomic, big data discourse, or system dynamics approaches independently, this research combines textual big data analysis and causal loop modeling to address gaps identified in prior methodologies. Specifically, we analyze social discourses and sentiments related to low fertility through text mining of social media data, and then link these qualitative insights with quantitative simulations using system dynamics. Our integrated approach offers a novel methodological framework that enhances understanding of the complex interactions between societal perceptions, policy interventions, and demographic outcomes. The results underscore the importance of capturing both qualitative social trends and quantitative policy feedback loops, providing valuable implications for designing more effective fertility-enhancing policies.

Keywords: Topic Modelling; System Dynamics; Low Fertility Rate; Integrated Approach.

RESUMEN

Este estudio examina los aspectos multidimensionales de la baja fertilidad mediante la integración de la minería de textos de big data con el análisis de dinámica de sistemas. Mientras que la investigación anterior utilizó principalmente enfoques macroeconómicos, de discurso de big data o de dinámica de sistemas de forma independiente, esta investigación combina el análisis textual de big data y el modelado de bucles causales para abordar las lagunas identificadas en las metodologías anteriores. Específicamente, analizamos los discursos sociales y los sentimientos relacionados con la baja fertilidad a través de la minería de texto de los datos de las redes sociales, y luego vinculamos estos conocimientos cualitativos con simulaciones cuantitativas utilizando la dinámica de sistemas. Nuestro enfoque integrado ofrece un marco metodológico novedoso que mejora la comprensión de las complejas interacciones entre las percepciones sociales, las intervenciones políticas y los resultados demográficos. Los resultados subrayan la importancia de captar tanto las tendencias sociales cualitativas como los bucles de retroalimentación cuantitativos de las políticas, y aportan valiosas implicaciones para diseñar políticas de fomento de la fertilidad más eficaces.

Palabras clave: Modelización Tópica; Dinámica de Sistemas; Baja Tasa de Fecundidad; Enfoque Integrado.

INTRODUCTION

The issue of low birthrates is a significant demographic challenge faced by many countries, including South Korea, profoundly impacting national competitiveness and sustainability from a long-term perspective. South Korea currently records one of the lowest birth rates globally, posing substantial risks such as rapid population aging, labor shortages, increased welfare expenditures, and intensified social conflicts. The phenomenon of low birthrates is a complex, structural issue that cannot be resolved merely through policies encouraging childbirth, as it involves multidimensional interactions across economic, social, cultural, and political domains.

Recently, studies utilizing big data, machine learning, and text mining techniques have actively explored the core themes and potential factors of low birthrate discourse. Such approaches have the advantage of extracting meaningful information and patterns from vast amounts of online texts or administrative data, identifying practical issues difficult to capture through traditional surveys or limited case studies. However, big data analysis alone struggles to fully grasp structural and dynamic problems and faces limitations in interpreting the complex causal relationships and feedback mechanisms among various factors.

As an alternative, system dynamics has garnered attention as an effective approach to structurally analyze complex social issues and predict future changes through simulation. Using causal loop diagrams (CLDs) and feedback loop analyses, system dynamics intuitively visualize and clarify the causes, consequences, and interactions among variables related to low birthrates. Integrating qualitative and quantitative information from big data analyses into system dynamics causal loop models facilitates a comprehensive understanding of how social, administrative, and political issues stemming from low birthrates could be reinforced or mitigated. Thus, this research aims to explore an integrated approach to the issue of low birthrates through the combined use of big data-based topic modeling and system dynamics.

Addressing the issue of low birthrates requires more than isolated policies like expanding childbirth subsidies or childcare facilities; it necessitates a structural understanding of root causes and inter-sectoral policy coordination. Previous demographic or economic studies predominantly conducted empirical analyses focusing on specific factors (e.g., income levels, educational environments, work-life balance systems), lacking comprehensive consideration of interactions among individual factors. Particularly, big data-based topic modeling proves highly effective for macro-level identification of how low birthrate-related discourse evolves and what social and policy issues emerge as primary concerns. Furthermore, integrating the key variables and factors identified through topic modeling into a system dynamics model to construct causal loops and feedback structures enables simulation of structural characteristics and medium-to-long-term impacts. Therefore, an integrated approach combining big data analysis and system dynamics presents new possibilities for understanding and resolving low birthrate issues.

The objective of this study is to predict the social, administrative, and political issues of low birthrate countries through big data-based topic modeling and system dynamics. Specifically, the detailed objectives are as follows: a. Identify core issues, discourse structures, and critical factors related to low birthrates using big data-based topic modeling. b. Apply identified key factors to the system dynamics approach to design causal loop diagrams and feedback loop structures. c. Using causal loop analyses, clarify the structural mechanisms of social, administrative, and political problems caused by low birthrates and predict their long-term ripple effects. d. Based on analytical results, present policy implications and sustainable measures, contributing to the formulation of integrated strategies addressing low birthrate issues.

The research questions for this study are:

- Research Question 1: what social, economic, and political domains are central to the core low birthrate-related topics extracted from big data text materials, and what are their characteristics?
- Research Question 2: what types of feedback loops do the key factors (variables) derived from topic modeling form within the system dynamics causal loop diagram, and how do these affect the low birthrate issue?
- Research Question 3: from a structural analysis perspective based on causal loops, what are the long-term social, administrative, and political issues induced by low birthrates, and what critical intervention points can mitigate or transform these issues through policy interventions?

Literature Review and Originality of this Study

Review of Prior Studies

The issue of low birth rates has emerged as a critical demographic and social challenge worldwide, prompting diverse academic perspectives and methodologies (Lee & Mason, 2021; Bloom et al., 2020). This chapter reviews recent international studies, categorizing them into four distinct groups based on their research topics and methodologies. Through this review, we aim to identify the significance and limitations of the approach integrating big data-based topic modeling and system dynamics adopted in this study, thus highlighting its distinctiveness.

- Firstly, studies adopting macro-level and policy-oriented approaches to low birth rates are discussed. Jonas and Morgan (2020) analyzed low fertility and aging populations in major developed

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countries such as the United States, France, and Japan through macroeconomic models. They assessed the impacts of policy indicators like welfare expenditures, job creation, and childbirth incentives on national fiscal stability from a time-series perspective (Sánchez-Romero et al., 2021; Lee & Ogawa, 2022). While these studies primarily utilized econometric approaches to examine long-term correlations between policies and birth rates (Holzmann & Hinz, 2022), they did not actively incorporate big data or system dynamics, marking a methodological limitation.

- Secondly, big data-based discourse analysis approaches to low birth rates are reviewed. Smith (2021) employed text mining techniques to analyze big data from social media and online communities, capturing social discourses and emotional dimensions related to low fertility. This approach is advantageous in analyzing individuals' spontaneous and everyday opinions, which are typically not reflected in conventional statistical data (Lazer & Radford, 2019; Jaidka et al., 2020). Commonly used analytical methods include topic modeling, sentiment analysis, and social network analysis, characterized by large-scale and time-series data (Rahman et al., 2022; Wang & Zhang, 2021). However, these studies often lack causal interactions among policy variables or integration with simulation approaches.
- Thirdly, system dynamics-based demographic simulation approaches are examined. Johnson and Anders (2019) used system dynamics to analyze long-term impacts of low fertility, such as reduced labor force and increased welfare expenditures. They assessed policy variables like childcare infrastructure expansion and improvement in women's employment rates through various scenarios (Zhou et al., 2020; Sterman, 2018; Forrester, 2019). Methodologies primarily employed Stock & Flow Diagrams and Causal Loop Diagrams for simulation, with few instances of integration with big data.
- Finally, integrated approaches combining big data and policy modeling are explored. Chen and Wu (2022) linked social factors derived from text mining with policy equilibrium models to analyze changes in social perceptions and fertility intentions. Their study integrated qualitative and quantitative analyses using variables like housing prices, education costs, and marriage age (Hu & Lin, 2022; Kim et al., 2021). However, this research differs from the current study as it did not actively utilize system dynamics' causal mapping and feedback loop structures.

In contrast to previous studies, this research aims to comprehensively analyze low fertility by integrating big data-based text mining results with causal mapping and feedback loop analysis of system dynamics.

Summary of Key Variables in this Study

The issue of low fertility involves complex interactions among economic factors (income, housing costs, female employment rate), socio-cultural factors (perceptions of marriage and childbirth, family-friendly culture), and political-administrative factors (birth incentives, childcare budget, parental leave). Reflecting this complexity, this study establishes four major variable groups and constructs a Causal Loop Diagram (CLD):

- Firstly, Economic and Employment Variables (employment rate, unemployment rate, household income, housing costs, female labor force participation rate).
- Secondly, Welfare and Administrative Variables (number of childcare facilities, childcare budget, parental leave usage rate, childbirth incentives).
- Thirdly, Socio-cultural Variables (social perceptions of marriage and childbirth, work-family balance culture, gender conflicts).
- Fourthly, Political and Policy Variables (government fiscal soundness, policy priorities, pension and public healthcare burden).

The study systematically analyzes structural interactions through feedback loops by qualitatively and quantitatively linking keywords derived from big data-based topic modeling with these variables.

Originality of this Study

Compared to existing studies, this research presents the following distinctiveness: firstly, it integrates qualitative and quantitative data simultaneously by combining big data analytics and system dynamics methodologies. Secondly, it includes multi-layered variables from socio-cultural and political-administrative dimensions, in addition to economic indicators and demographic data, thereby providing specific governance and policy linkages for addressing low fertility.

Research Design

To facilitate a deeper understanding of Korea's low fertility phenomenon, this study aims to integratively analyze academic papers related to low fertility published over the past 25 years (2000-2024) using big data analysis and topic modeling techniques. The findings will be connected to major variables (economic and employment, socio-cultural, welfare and administrative, political and policy) and reflected in a System

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Dynamics Causal Loop Diagram (CLD). The research design consists of four main stages: data collection and preprocessing, text analysis (topic modeling), integration of themes with key variables, and application of system dynamics.

Data Collection and Preprocessing

During data collection, scholarly articles from Korean academic databases (KCI) from 2000 to 2024 were identified using search terms related to low birthrate (eg. low fertility, low birthrate, population decline) within titles and abstracts. The collected data underwent morphological analysis using KoNLPy, followed by preprocessing steps such as removal of stopwords, duplicate documents, and irrelevant noise (advertisements, captions, etc.) to ensure suitability for analysis.

Text Analysis (Topic Modeling)

The study applied Latent Dirichlet Allocation (LDA), a prominent topic modeling technique, to the collected and preprocessed data. Additionally, alternative models such as Non-negative Matrix Factorization (NMF) or Dynamic Topic Modeling (DTM) were considered based on the data's characteristics. The analysis began by constructing a text corpus from abstracts and article contents, followed by basic statistical analyses such as tokenization, word frequency, and TF-IDF. Optimal topic numbers were determined using coherence and perplexity metrics. Model training was performed on individual and integrated datasets, and interpretation involved extracting representative keywords and sentences per topic, further enriched through topic similarity analysis, PF-net analysis, and clustering analysis. The software used in this study is Netminer 4.5.

Integrated Theme Extraction and Key Variable Linkage

Major topics derived from text analysis were reclassified and linked to the key variables—economic-employment, socio-cultural, welfare-administrative, and political-policy—as defined by the study. For instance, topics related to 'parental leave' and 'childcare infrastructure' were linked to welfare-administrative variables, whereas 'youth unemployment' and 'income disparity' connected to economic-employment variables. Newly identified variables, such as those related to 'housing and real estate,' were also included as expanded integrated themes. Hypothetical causal frameworks were then developed by establishing relationships between variables suitable for system dynamics modeling. Examples include reinforcing (+) relationships such as 'rising housing costs → delayed marriage among youth → lower birth rates,' and balancing (-) relationships like 'expansion of childcare facilities → reduced childcare burden → mitigation of declining birth rates.' Furthermore, feedback structures among key variables were proposed and structured into positive feedback loops (R+) and negative feedback loops (R-).

Application of System Dynamics

Based on the integrated themes and key variables, a Causal Loop Diagram (CLD) was created using system dynamics methodology. This process incorporated previously identified variables and relationships, as well as newly discovered issues from text analysis. The design clearly identified reinforcing and balancing feedback loops, enabling a structural understanding of the low fertility issue and the derivation of policy implications. The software used for CLD here in this study is Vensim.

Analysis

Results of Topic Modeling Analysis

Among the academic papers published in Korea from 2000 to 2024, a total of 386 papers include the keyword "low birthrate" in their titles. Using these papers, the English abstracts were analyzed. First, a word cloud analysis was conducted on the words included in the selected abstracts to gain basic insights. The results of the word cloud analysis are shown in figure 1 below.

This word cloud indicates that in addressing the issue of low birthrate, policy responses, socio-economic background, national concerns, and academic research methodologies are all considered important. It suggests that low birthrate is recognized not merely as a demographic issue but as a multidimensional and complex social problem.

To facilitate the analysis, only words that appeared more than 20 times were included. Figure 2 presents the results of a concentric circle analysis of the frequently occurring keywords. The concentric circle analysis visually represents the level of centrality of keywords related to the low birthrate issue. The closer a keyword is to the center of the circle, the higher its centrality within the network, indicating it is a core keyword.

The results of this analysis show that the core causes and related topics of the low birthrate issue—such as "gender inequality," "childcare and caregiving issues," and "burdens in student and work environments"—are closely interconnected. These core keywords demonstrate the complex interplay of various social and economic factors surrounding the issue.

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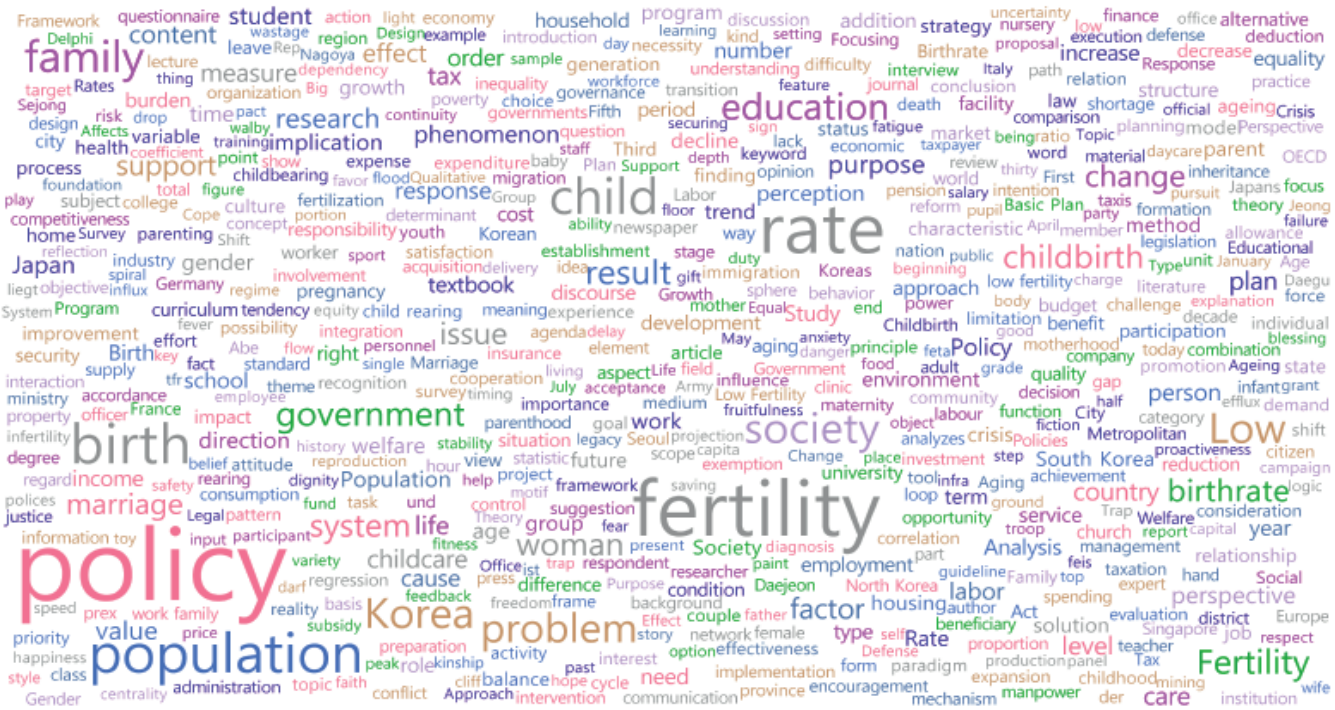

Figure 1. Word Cloud Analysis of Keywords from Abstracts of Papers Related to Low Birthrate

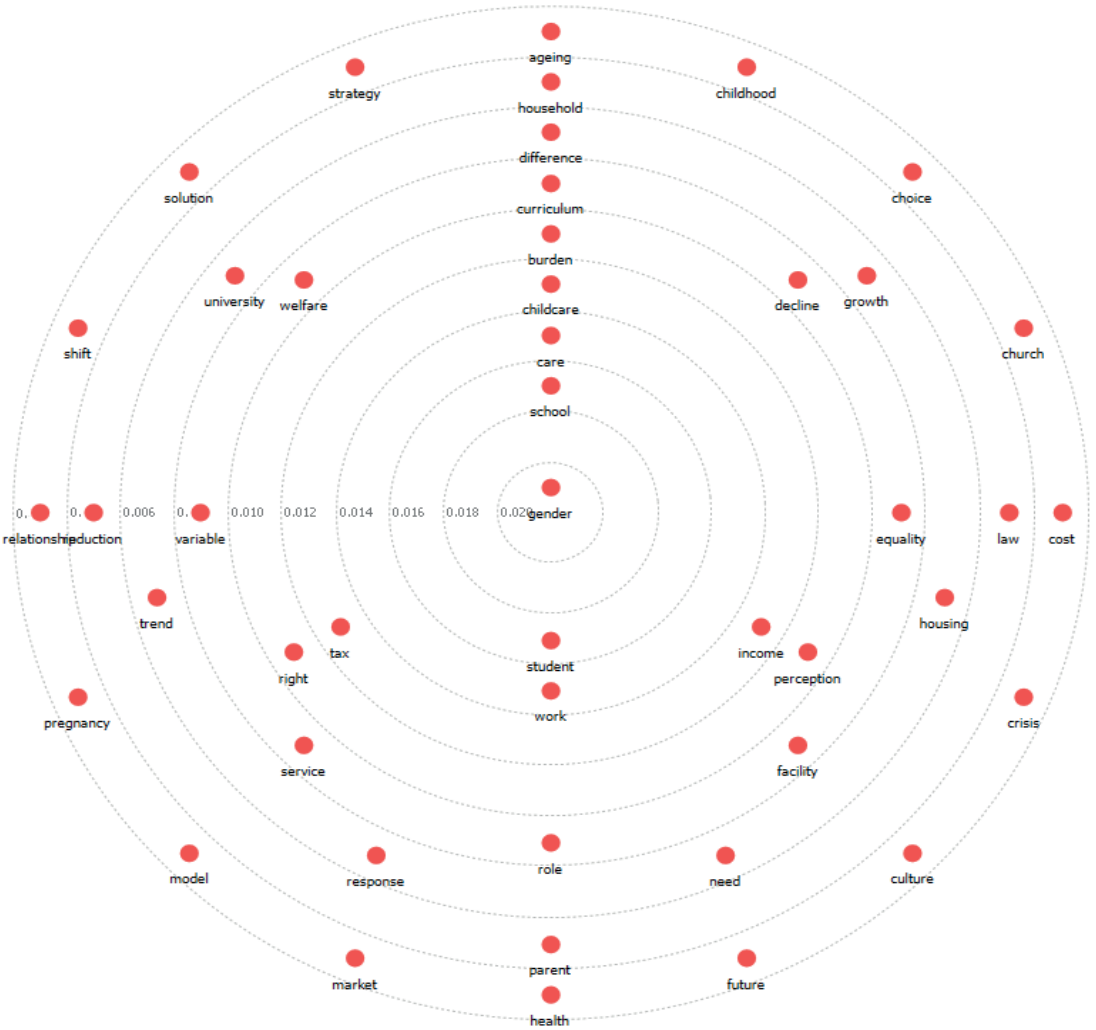

Figure 2. Results of Concentric Circle Analysis

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The figure below shows the results of a degree centrality analysis of the keywords extracted in relation to the low birthrate issue, and the statistical values for centrality are presented in figure 3. The presented degree centrality analysis table displays both the in-degree and out-degree centrality values of keywords related to the low birthrate issue.

As shown in the figure, Gender exhibits the highest centrality in both in-degree and out-degree values, indicating that it is the most central node in the network. In other words, the table clearly demonstrates that gender serves as the key connecting point in the low birthrate issue network, around which major social factors such as students, school, caregiving, and work are most prominently discussed.

		1	2
		In-Degree Centrality	Out-Degree Centrality
1	gender	0.022485	0.022485
2	student	0.017699	0.017699
3	school	0.016615	0.016615
4	care	0.016047	0.016047
5	work	0.015362	0.015362
6	income	0.014076	0.014076
7	childcare	0.013310	0.013310
8	tax	0.012573	0.012573
9	burden	0.011831	0.011831
10	right	0.011507	0.011507
11	perception	0.011403	0.011403
12	facility	0.009772	0.009772
13	curriculum	0.008995	0.008995
14	welfare	0.008891	0.008891
15	variable	0.008871	0.008871
16	service	0.008388	0.008388
17	role	0.008332	0.008332
18	decline	0.008084	0.008084
19	equality	0.007885	0.007885
20	university	0.007778	0.007778
21	trend	0.007163	0.007163
22	growth	0.006930	0.006930
23	difference	0.006707	0.006707
24	need	0.006176	0.006176
25	housing	0.006143	0.006143
26	response	0.005715	0.005715
27	law	0.005420	0.005420
28	household	0.005093	0.005093
29	reduction	0.005018	0.005018
30	parent	0.003831	0.003831

Figure 3. Degree Centrality in the Low Birthrate Issue Network

Meanwhile, although the degree centrality values were derived and the centrality network was reviewed, the resulting network structure appeared overly complex. To simplify this, a PFnet (Pathfinder Network) analysis was conducted, and the results of this analysis are shown in figure 4 below. This analysis allows for a clearer and more concise understanding of the interconnections among keywords related to the low birthrate issue.

As shown in the figure, keywords such as gender, student, care, and work occupy large and central positions. In particular, gender functions as a core node, playing a central role and connecting with various other keywords. The connections between keywords appear in a linear and simplified structure, allowing each keyword group to be more clearly distinguished.

The PFnet analysis illustrates a structure in which various socio-economic factors interact around core keywords like gender, student, care, and work. These results clearly demonstrate that the low birthrate issue is intricately linked with various social and economic factors such as gender inequality, the balance between work and caregiving, economic burdens, educational challenges, and policy responses. It suggests that these central connection points should be given priority consideration in both policy and academic discussions.

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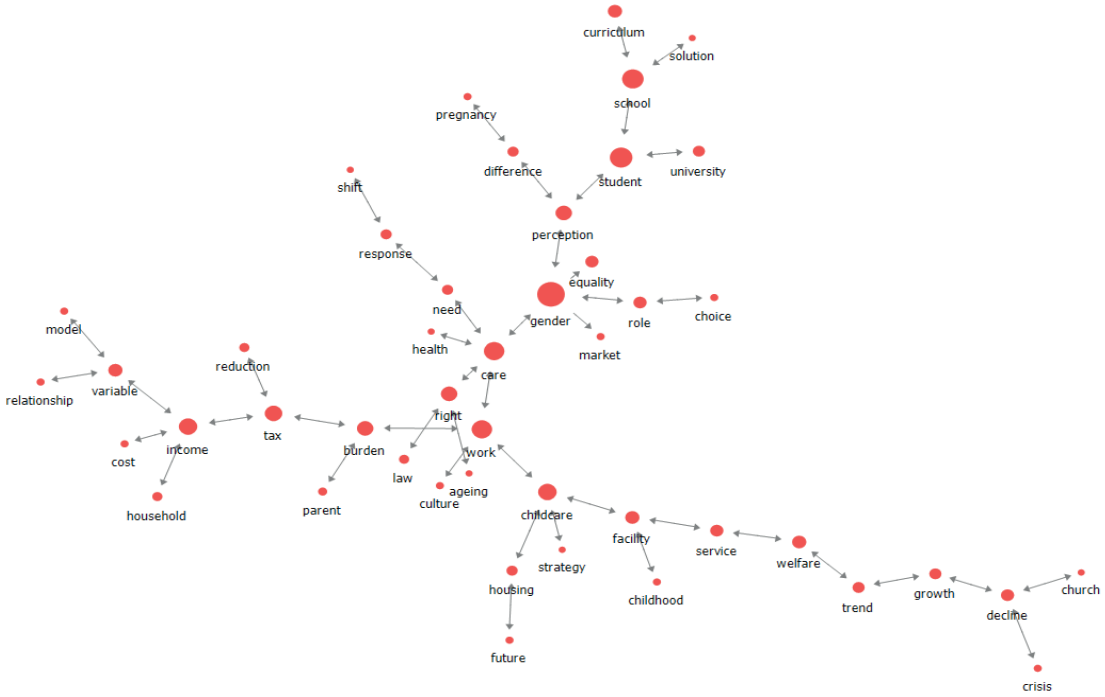

Figure 4. PFnet Analysis Results of the Low Birthrate-Related Network

A clustering analysis was subsequently conducted based on the results, and the outcomes are shown in figure 5. As seen in the figure, the keywords are clearly divided into eight distinct groups based on thematic relevance. Some keywords—such as care, gender, culture, and health—play a bridging role between different groups and are positioned centrally within the network. The lines connecting clusters indicate that the major keyword groups are not independent but are interlinked, reflecting the complex and interconnected nature of the low birthrate issue.

This figure presents the results of visualizing the low birthrate issue through PFnet analysis, followed by clustering to group related keywords. The overall characteristics and key features of each cluster can be described as follows. The keywords are organized into eight clearly defined thematic groups. Some keywords—such as care, gender, culture, and health—serve as connecting nodes between multiple groups and occupy central positions. The lines showing connections between clusters illustrate that the major keyword groups are not independent but are interrelated, highlighting the complex and interconnected nature of the low birthrate issue. The characteristics of each group are summarized below:

1. Group G1: Care and Social Rights Cluster.
    - Main Keywords: care, health, rights, aging, change, need, law, response.
    - Characteristics: this group emphasizes the social burden and rights-related aspects of low birthrate, highlighting the need for caregiving, the challenges of an aging population, and the necessity of policy responses to these issues.

2. Group G2: Education and Youth Cluster.
    - Main Keywords: student, school, university, curriculum, solution.
    - Characteristics: this group focuses on the educational environment of the younger generation and strategies for addressing the low birthrate through education. It underscores the importance of educational approaches to resolving low fertility among youth.

3. Group G3: Economic Factors Cluster.
    - Main Keywords: income, tax, decline, cost, family, parent, burden, variable, relation, model.
    - Characteristics: this group captures the economic burdens that impact low birthrate, stressing the need for policy approaches to alleviate financial pressures, such as addressing income and tax-related issues.

4. Group G4: Gender Equality and Social Roles Cluster.
    - Main Keywords: gender, equality, role, choice, market.
    - Characteristics: this cluster highlights the importance of gender issues and equal social roles. It emphasizes that gender imbalance and women's right to choose significantly influence the low birthrate issue.

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5. Group G5: Childcare and Infrastructure Support Cluster.
    - Main Keywords: childcare, facility, housing, future, childhood.
    - Characteristics: this group centers on the need to build infrastructure supporting childbirth and childrearing, such as childcare facilities and housing. It reflects the necessity for tangible support to overcome low birthrate.

6. Group G6: Culture and Policy Response Cluster.
    - Main Keywords: culture, strategy.
    - Characteristics: this cluster stresses the importance of cultural approaches to the low birthrate phenomenon, the need for a shift in social perception, and the importance of strategic policy responses. Culture plays a central role, linking with several other groups.

7. Group G7: Service and Welfare-Oriented Approach Cluster.
    - Main Keywords: welfare, service, trend, growth.
    - Characteristics: this group emphasizes expanding social welfare services to address low birthrate and the necessity of reversing population decline trends through these services.

8. Group G8: Crisis Perspective Cluster.
    - Main Keywords: crisis, decline, religion.
    - Characteristics: this cluster frames low birthrate as a social crisis and highlights population decline as a serious issue. It also indirectly suggests the possibility of addressing the issue through religious perspectives.

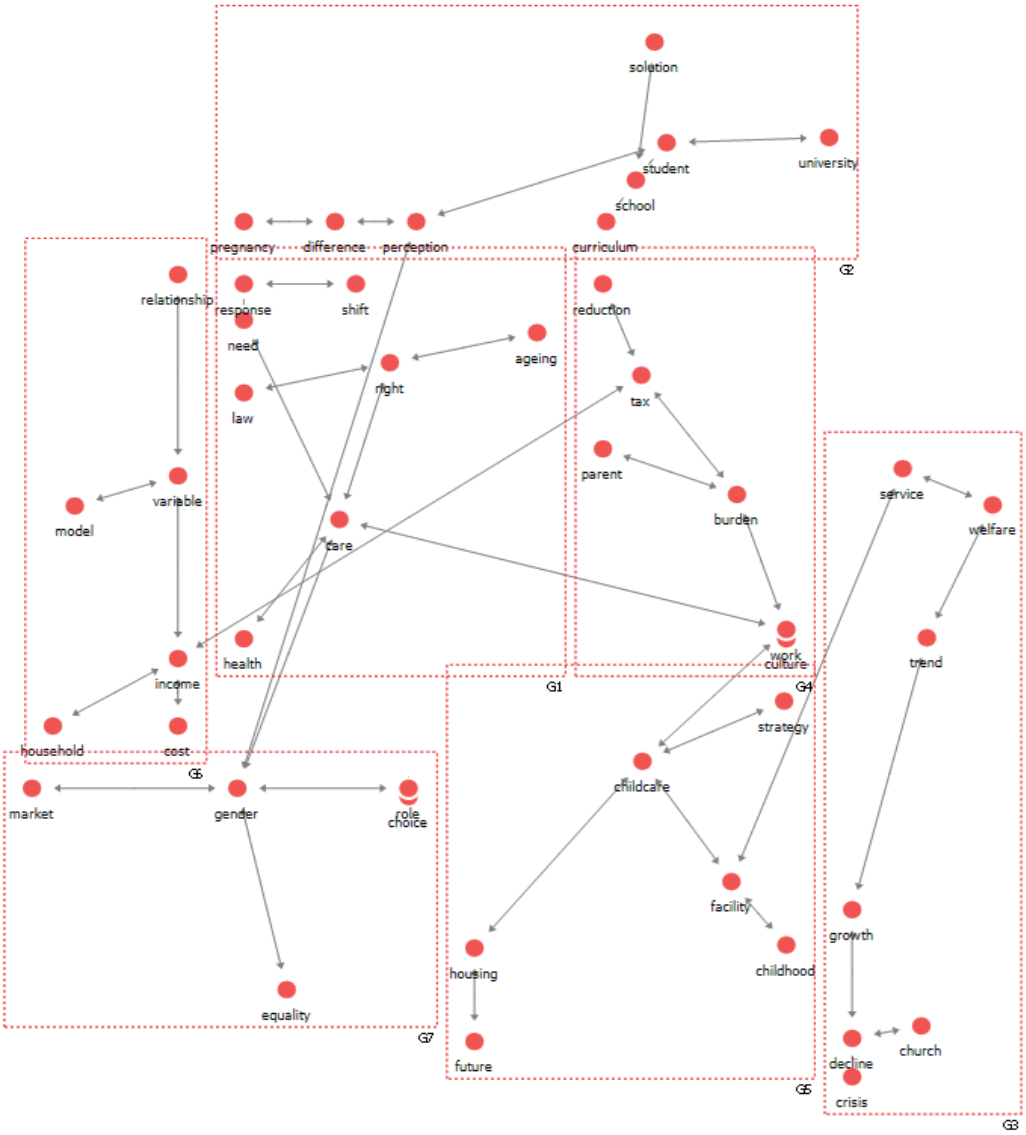

Figure 5. Major Clusters of the Low Birthrate Issue

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System Dynamics Analysis

Key terms derived from the topic modeling analysis were incorporated as variables in the causal loop diagram of the system dynamics model. The names and descriptions of each variable are presented in the table below.

Variable Names and Descriptions

The names and descriptions of the variables included in the causal loop diagram are shown in table 1 below.

Table 1. Variable Names and Descriptions Included in the Causal Loop Diagram

No	Variable	Description
1	strategy	Establishment of long-term governmental and societal strategies and plans to respond to low birth rates
2	childcare	Policies and programs related to childcare support and childcare services
3	facility	Quantitative and qualitative standards of facilities (e.g., daycare centers, kindergartens) for childcare and education
4	service	Level of provision of social services related to childcare, caregiving, and welfare
5	welfare	Overall level of social welfare and supporting policies
6	trend	Socially spreading childbirth-friendly trends and atmosphere
7	growth	Degree of population growth and enhancement of society's growth potential
8	decline	Mitigation of low birth rate phenomenon or reduction in population decline
9	crisis	Level of social crisis caused by low birth rates
10	housing	Level of improvement in housing conditions, including stability, affordability, and environment
11	childhood	Quality of life and environmental conditions during infancy and childhood
12	future	Expectations for quality of life of future generations and societal sustainability
13	market	Employment opportunities and working conditions in the labor market
14	gender	Level of social disparities and discrimination based on gender
15	equality	Level of gender equality in society
16	choice	Degree of guaranteeing individuals' autonomy in life, childbirth, and childcare decisions
17	role	Degree and rigidity of socially expected gender roles
18	ageing culture	Level of societal ageing and intensification of ageing culture
19	burden	Social and economic burden resulting from ageing
20	tax	Level of taxation and public burden due to increased societal responsibilities
21	income	Average household income level
22	cost	Household cost of living and economic burden level
23	reduction	Degree to which increased household economic burden reduces the intention to have children
24	model	Degree of maintenance or change in traditional marriage and childbirth models
25	relationship	Degree of maintenance or change in family and social relationship structures
26	perception	Social awareness level about low birth rates and birth-friendly policies
27	difference	Degree of change in social perceptions and disparities
28	pregnancy	Social perception and acceptance levels toward pregnancy and childbirth
29	shift	Degree of societal change in responses and attitudes to low birth rates
30	response	Level of society's childbirth-friendly response and active policy formulation
31	need	Degree of societal demand and necessity for childcare and caregiving services
32	care	Level and qualitative improvement of childcare and caregiving services provided
33	health	Degree of improvement in health, medical care, and welfare
34	work	Quality of working conditions, workplace environment, and the degree of work-family compatibility
35	life	Achievement of individuals' quality of life and work-life balance
36	flight	Level of job withdrawal and labor market dropout
37	curriculum	Level of educational curriculum and content provided by schools and educational institutions

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38	school	Quality and enhanced role of schools and public education
39	solution	Ideas and capacities gained through education to address the low birth rate issue
40	student	Level and potential of human resources among students and youth
41	university	Educational environment and support quality at universities and higher education institutions

Construction of the Causal Loop Diagram and Relationship Setting Between Variables

Construction of the Causal Loop Diagram

The basic structure of the causal loop diagram, which includes the causes of low birthrate and potential solutions, was established as shown in figure 6 below.

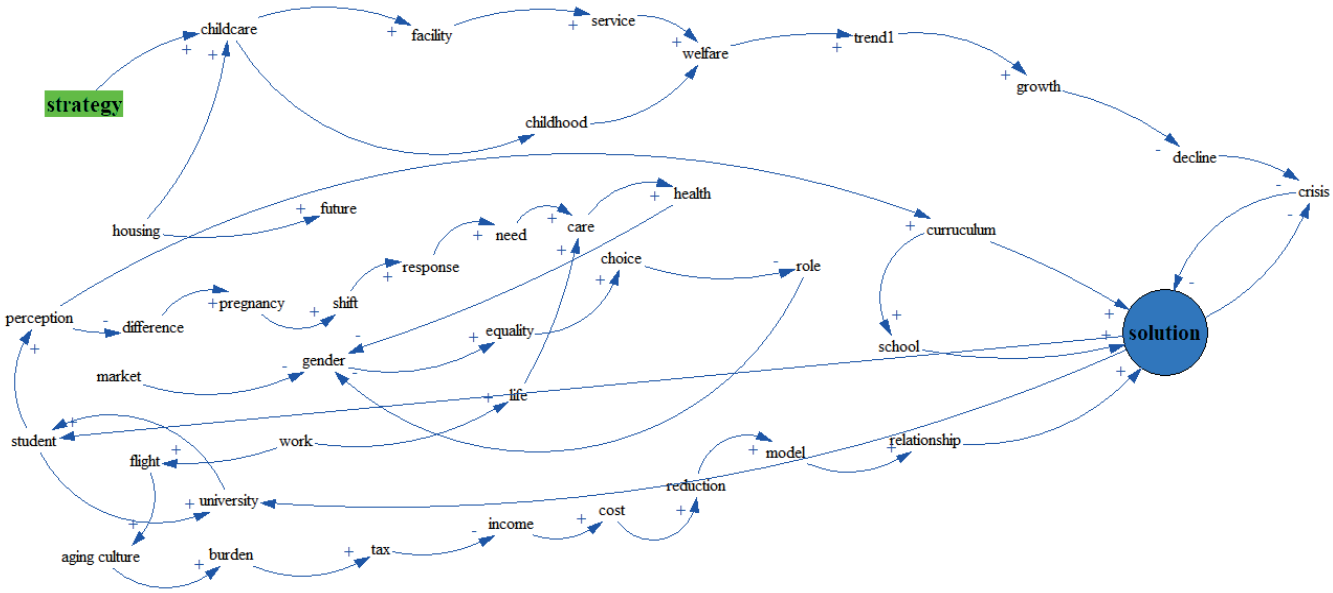

Figure 6. Basic Structure of the Causal Loop Diagram

Relationships Between Variables

Meanwhile, the causal relationships between the variables were established based on big data analysis results and previous studies, as outlined below:

Childcare Support and Living Environment Structure

strategy → (+) childcare → (+) facility → (+) service → (+) welfare → (+) trend → (+) growth → (-) decline → (-) crisis

Strategic policies lead to improved childcare policies, which enhance childcare facilities and expand social services, raising overall welfare levels. This creates a birth-friendly trend, contributes to population growth, reduces the low birthrate issue, and ultimately eases the population crisis.

Housing and Future Vision Environment

housing → (+) childcare

housing → (+) future

facility → (+) childhood → (+) welfare

Improved housing stimulates childcare policy activation and enhances quality of life in the future. Improved childcare facilities lead to better early childhood environments, contributing to higher levels of welfare.

Gender Equality and Labor Market Structure

market → (-) gender → (+) equality → (+) choice → (-) role → (-) gender (feedback loop)

Improvements in the labor market reduce gender disparity, which increases gender equality and expands individual autonomy in decision-making, thereby reducing traditional role expectations and further narrowing gender gaps.

Aging and Increasing Social Burden Structure

ageing culture → (+) burden → (+) tax → (-) income → (+) cost → (+) reduction → (+) model → (+) relationship

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The increase in aging culture leads to a rise in social burdens, which increases tax pressures, reduces household income, and raises living costs. This reduces fertility intentions, causes changes in marriage and childbirth models, and alters social relationships.

Shift in Social Perceptions Structure

perception → (-) difference → (+) pregnancy → (+) shift → (+) response → (+) need → (+) care → (+) health → (-) gender

student → (+) perception (feedback loop)

Improvements in social perception reduce disparities and promote positive views on pregnancy and childbirth, leading to changes in societal responses and strengthened support systems. This increases demand for caregiving services, improves health, and reduces gender disparity. Enhancing student capabilities also feeds back into improving societal perception.

Work-Life Balance Structure

work (worsened) → (+) flight → (+) ageing culture

work (improved) → (+) life → (+) care

Poor working conditions lead to labor market withdrawal and increased aging, while better working conditions improve quality of life and increase demand for caregiving services.

Education and Human Resource Structure

curriculum → (+) school → (+) solution → (+) student → (+) university → (+) student (feedback loop)

Improvements in curricula strengthen school education, leading to more solutions for low birthrate issues. This enhances student capacity and improves higher education, which in turn further strengthens student capabilities.

Feedback Loops

From the causal loop diagram of the low birthrate issue, three reinforcing feedback loops and three balancing feedback loops were identified.

First, the reinforcing feedback loop is as follows:

R1: Gender Equality Promotion Reinforcing Loop

As shown in figure 7, the loop follows:

gender (-) → equality (+) → choice (+) → role (-) → gender (-)

This structure shows that a decrease in gender disparity promotes gender equality, which increases individual autonomy in decision-making, weakens traditional gender roles, and further reduces gender disparity, thus reinforcing the loop.

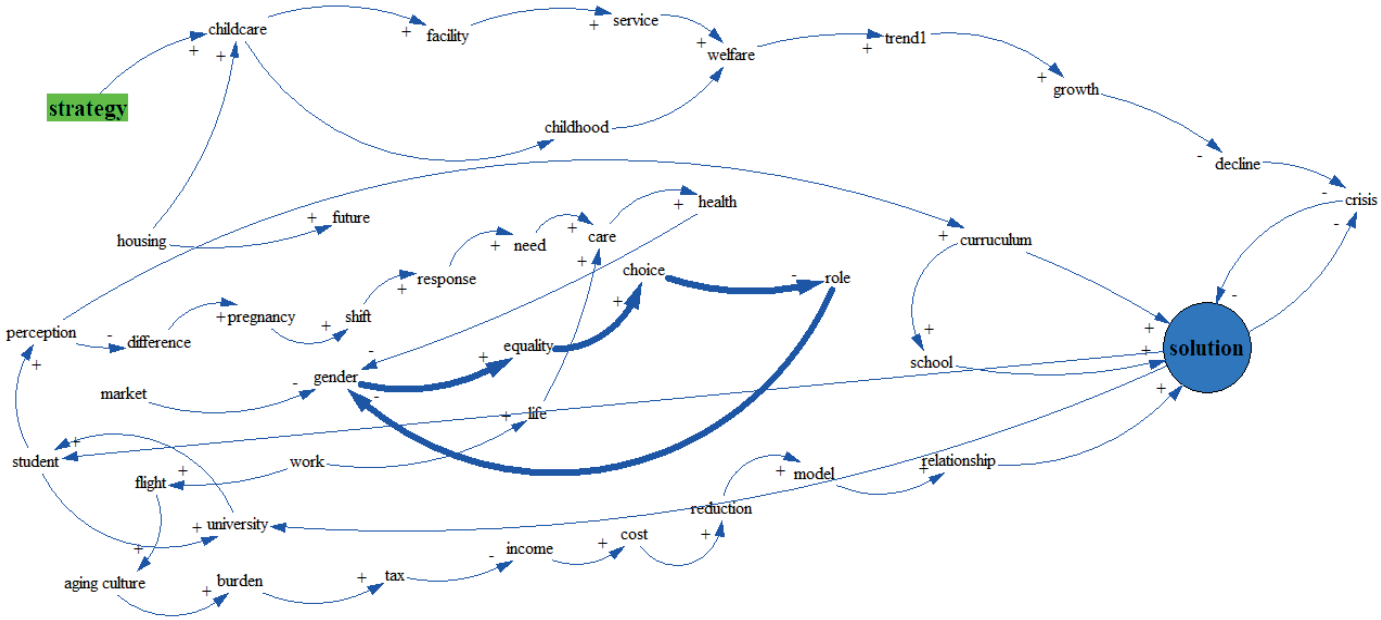

Figure 7. R1: Gender Equality Promotion Reinforcing Loop

R2: Childcare Environment Improvement Reinforcing Loop

As shown in figure 8 below, this loop follows the path:

childcare (+) → facility (+) → childhood (+) → welfare (+) → trend (+) → growth (+) → decline (-) → childcare (+)

This structure demonstrates that strengthening childcare policies leads to improved facilities and early childhood environments, fostering a birth-friendly atmosphere. In turn, this atmosphere further encourages the enhancement of childcare policies, forming a reinforcing cycle.

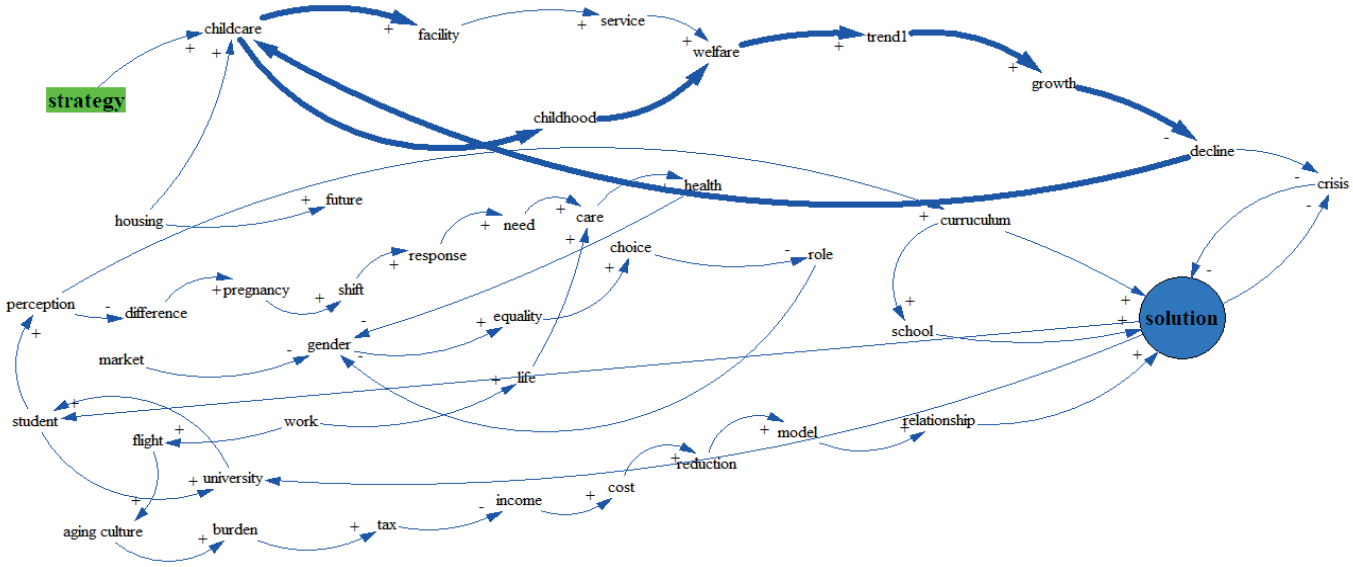

Figure 8. R2: Childcare Environment Improvement Reinforcing Loop

R3: Education-Perception Improvement Reinforcing Loop

As shown in figure 9 below, this loop follows the structure:

student (+) → perception (+) → difference (-) → pregnancy (+) → shift (+) → response (+) → need (+) → care (+) → health (+) → gender (-) → equality (+) → choice (+) → student (+)

This structure indicates that education and the empowerment of youth contribute to improving societal perceptions, which strengthens the response to pregnancy and childbirth issues. In turn, this enhanced response further promotes educational capacity, forming a reinforcing cycle.

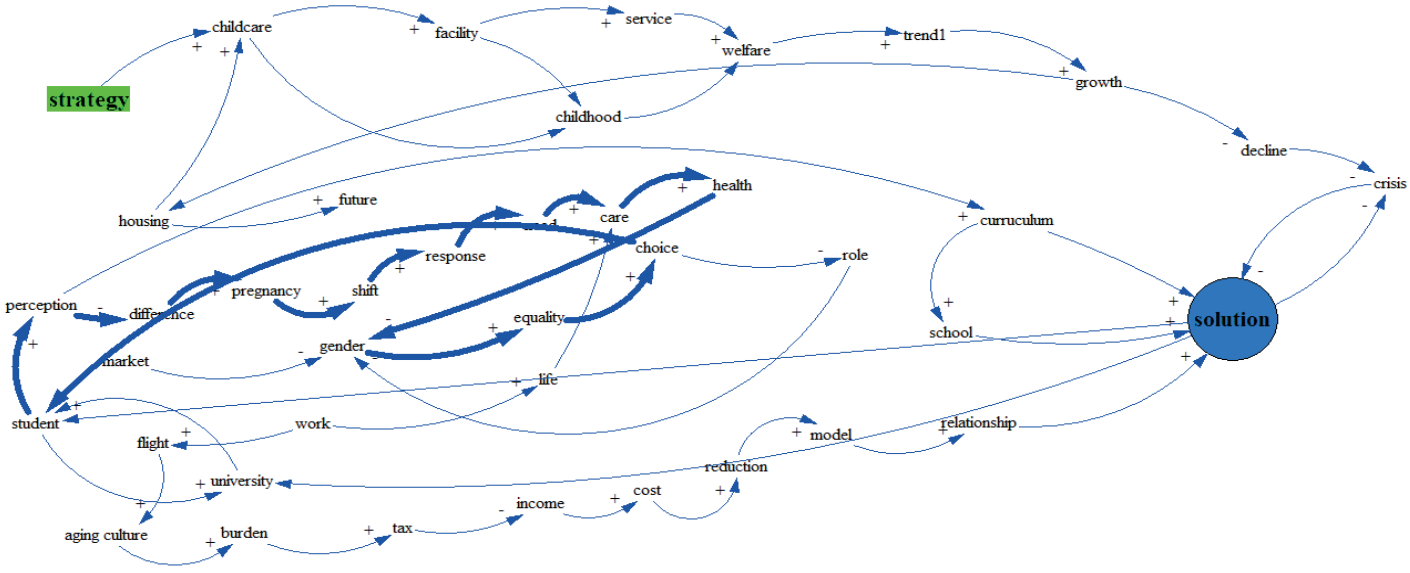

Figure 9. R3: Education-Perception Improvement Reinforcing Loop

Next, the balancing feedback loopsare as follows:

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B1: Social Burden Balancing Loop

As shown in figure 10 below, this loop follows the structure:

ageing culture (+) → burden (+) → tax (+) → income (-) → cost (+) → reduction (+) → model (+) → relationship (+) → ageing culture (-)

This structure illustrates that an increase in the burdens of an aging population leads, over the long term, to a decline in marriage and childbirth, which in turn weakens social relationships and ultimately acts to suppress further aging. Thus, the loop functions as a balancing mechanism.

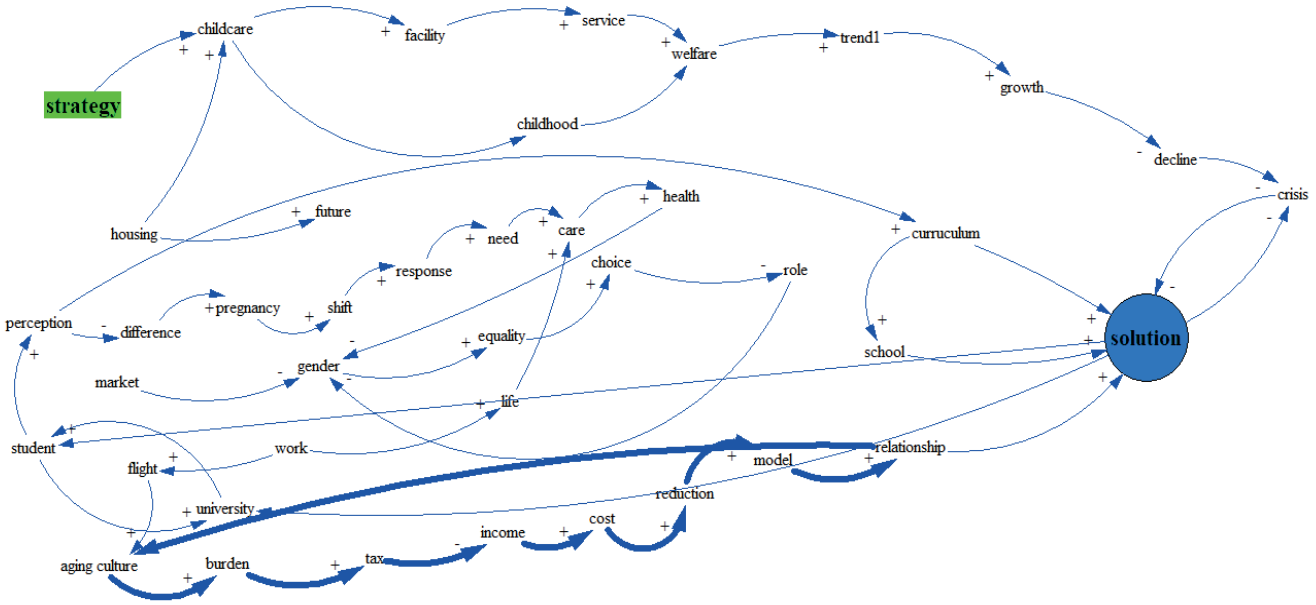

Figure 10. B1: Social Burden Balancing Loop

B2: Labor Environment Balancing Loop

As shown in figure 11 below, this loop follows the structure:

work (+) → flight (+) → ageing culture (+) → burden (+) → tax (+) → income (-) → cost (+) → reduction (+) → response (+) → need (+) → care (+) → life (+) → work (-)

This structure shows that a deterioration in working conditions leads to increased labor market exit and aging, which heightens social burdens. Ultimately, the resulting decline in quality of life promotes the need for improvement, driving efforts to enhance working conditions. Thus, the loop functions as a balancing feedback mechanism.

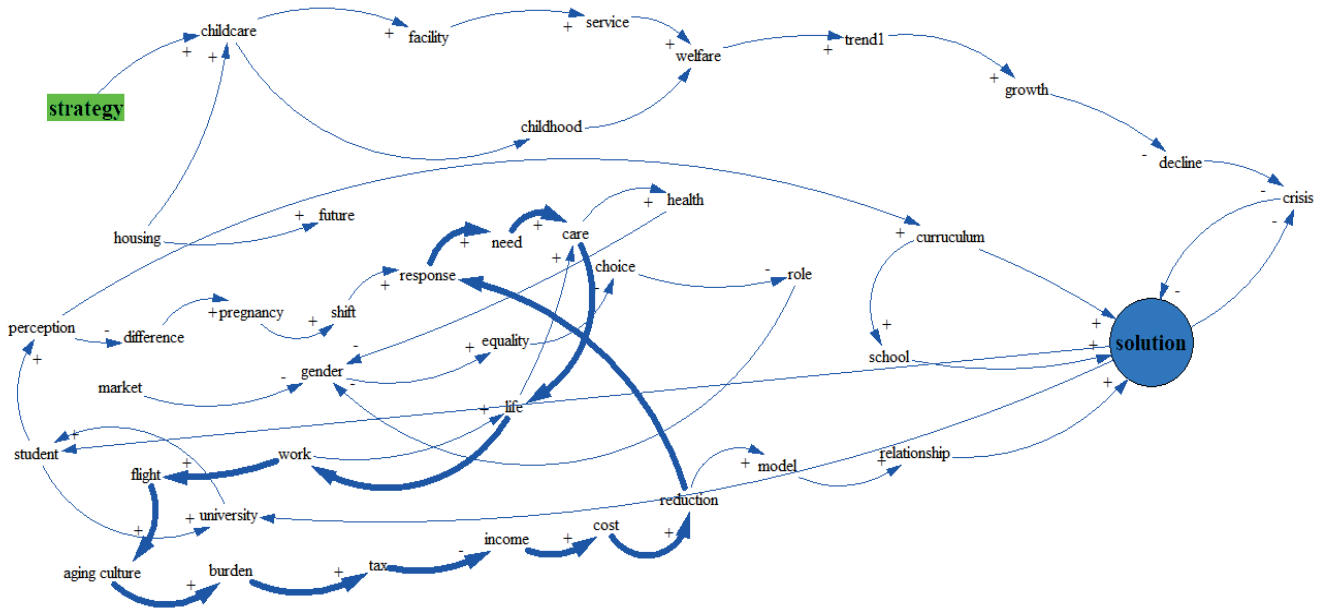

Figure 11. B2: Labor Environment Balancing Loop

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B3: Balancing Loop of Reduced Fertility Intentions Due to Economic Burden

As shown in figure 12 below, this loop follows the structure:

burden (+) → tax (+) → income (-) → cost (+) → reduction (+) → response (+) → need (+) → care (+) → health (+) → burden (-)

This loop illustrates that increasing economic burdens—through rising taxes and reduced household income—lead to higher living costs and decreased fertility intentions. However, this also triggers policy responses that increase caregiving services and improve health outcomes, ultimately helping to reduce the overall burden. Thus, the system balances itself through a compensatory mechanism.

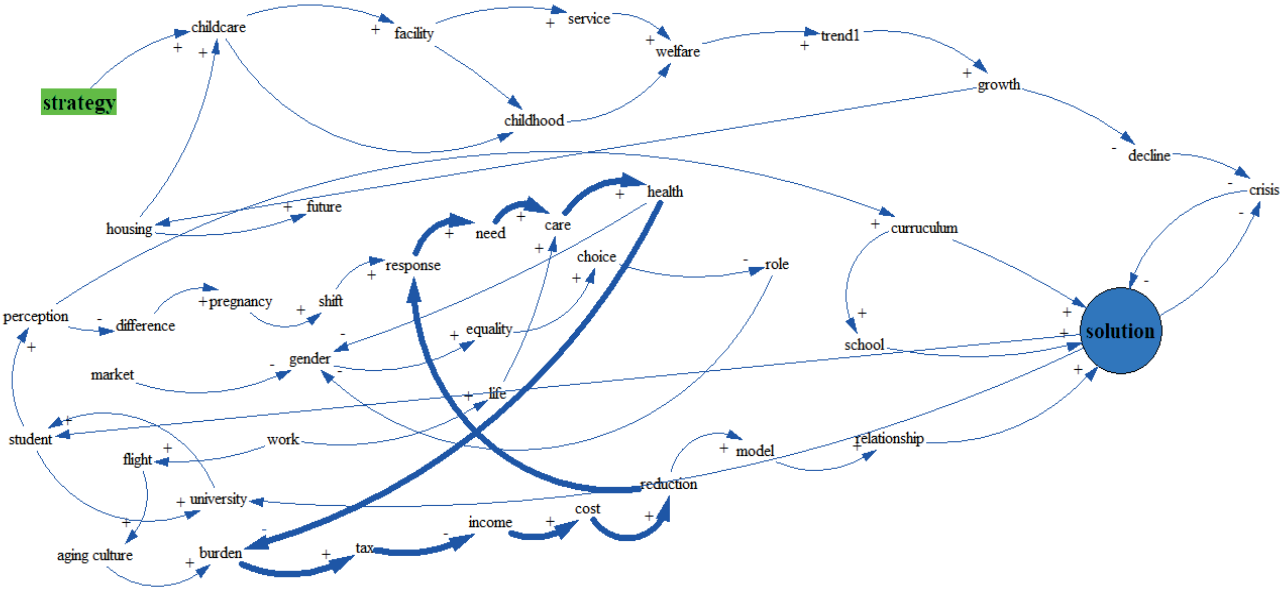

Figure 12. B3: Balancing Loop of Reduced Fertility Intentions Due to Economic Burden

Summary of Feedback Structures

The feedback structures discussed above are summarized in table 2 below.

Table 2. Summary of Feedback Structures

Loop Name	Loop Type	Structure
Gender Equality Promotion Reinforcing Loop	Reinforcing (R1)	gender (-) → equality (+) → choice (+) → role (-) → gender (-)
Childcare Environment Improvement Reinforcing Loop	Reinforcing (R2)	childcare (+) → facility (+) → childhood (+) → welfare (+) → trend (+) → growth (+) → decline (-) → childcare (+)
Education-Perception Improvement Reinforcing Loop	Reinforcing (R3)	student (+) → perception (+) → difference (-) → pregnancy (+) → shift (+) → response (+) → need (+) → care (+) → health (+) → gender (-) → equality (+) → choice (+) → student (+)
Social Burden Balancing Loop	Balancing (B1)	ageing culture (+) → burden (+) → tax (+) → income (-) → cost (+) → reduction (+) → model (+) → relationship (+) → ageing culture (-)
Labor Environment Balancing Loop	Balancing (B2)	work (+) → flight (+) → ageing culture (+) → burden (+) → tax (+) → income (-) → cost (+) → reduction (+) → response (+) → need (+) → care (+) → life (+) → work (-)
Balancing Loop of Reduced Fertility Intentions Due to Economic Burden	Balancing (B3)	burden (+) → tax (+) → income (-) → cost (+) → reduction (+) → response (+) → need (+) → care (+) → health (+) → burden (-)

Policy Implications

The following summarizes policy implications for addressing the low birthrate issue, based on the analysis of reinforcing and balancing feedback loops.

Policy Implications Derived from Reinforcing Feedback Loops

The first loop (R1) is the Gender Equality Promotion Reinforcing Loop, in which a reduction in gender disparity promotes gender equality, increases individuals' autonomy in decision-making, and weakens traditional gender

roles, thereby further reducing gender disparity. Based on this, the government should strengthen policies that address gender wage gaps in the labor market and support women with career interruptions. Additionally, legal and institutional measures must be established to ensure that both men and women can freely utilize parental leave and flexible work systems, thereby weakening the rigid stereotypes of traditional gender roles. Furthermore, the government should expand gender equality education in schools and workplaces to raise overall awareness and actively promote policies that eliminate widespread gender-discriminatory practices in society.

The second loop (R2) is the Childcare Environment Improvement Reinforcing Loop, where strengthened childcare policies lead to better facilities and early childhood environments, raising welfare levels and fostering a birth-friendly trend that ultimately contributes to an increase in birthrates. To support this, the government must make sufficient financial investments not only in expanding the quantity but also in improving the quality of public childcare facilities. Especially important is the expansion of accessibility to childcare and caregiving services so that all families can easily benefit from support. Welfare programs such as childcare allowances and child benefits should also be expanded, and childcare and welfare policies should be integrated into a comprehensive and effective support system.

The third loop (R3) is the Education–Perception Improvement Reinforcing Loop, where strengthened education for youth leads to improved social awareness, which enhances societal responsiveness to pregnancy and childbirth, thereby expanding gender equality and a birth-friendly environment. The government should incorporate family-friendly values and gender equality education into school curricula from adolescence to foster positive views on childbirth and family life. Moreover, higher education institutions should actively introduce childcare-friendly support systems, such as on-campus childcare facilities for students and faculty, to provide an environment supportive of childbirth and parenting. In addition, long-term, systematic public campaigns and awareness programs should be implemented to promote the importance of childbirth and family life, thereby fostering a more positive social atmosphere.

Policy Implications Derived from Balancing Feedback Loops

The first loop (B1) is the Social Burden Balancing Loop, which shows that as the burden from population aging increases, it leads to heavier economic pressure and decreased fertility intentions, as well as deteriorating social relationships. However, this eventually triggers a self-adjusting mechanism that helps relieve the aging pressure. To address this, the government should improve the efficiency of welfare and healthcare systems for the elderly and strengthen old-age income security systems to ease the intergenerational support burden on younger populations. Additionally, income support policies such as tax credits and direct cash transfers should be expanded to relieve the economic burden of childbirth and parenting, and financial support for families with multiple children should be strengthened.

The second loop (B2) is the Labor Environment Balancing Loop, where deteriorating working conditions lead to labor market exits and further population aging, increasing the social burden. To break this negative cycle, the government should promote labor policies such as reduced working hours and expanded flexible work arrangements to improve workers' quality of life and create an environment conducive to work–life balance. Supporting the activation of parental leave and providing tax incentives and benefits to family-friendly companies are also necessary to improve labor conditions. Moreover, policies that enhance employment stability and strengthen the social safety net should be reinforced to prevent labor force withdrawal.

The third loop (B3) is the Balancing Loop of Reduced Fertility Intentions Due to Economic Burden. In this structure, rising social burdens lead to reduced income and increased living costs, lowering fertility intentions. However, society eventually recognizes the crisis and responds by strengthening childbirth and caregiving services, which in turn improve public health and welfare and alleviate social burdens. Therefore, the government must take a proactive stance in expanding childbirth and caregiving support services to prevent declining fertility intentions in response to rising social burdens. It should continue to implement policies that improve public health and welfare and manage the long-term social burden.

CONCLUSIONS

This study conducted a multidimensional analysis of the fundamental causes of South Korea's serious low birthrate problem and sought effective countermeasures by applying big data-based Social Network Analysis (SNA) and system dynamics causal loop analysis. The main findings and their policy implications are as follows:

First, the big data analysis revealed that the key drivers of the low birthrate issue are deeply interconnected, including "lack of childcare support and living infrastructure," "gender disparity and labor market imbalance," "increasing social burdens," and "insufficient education and social awareness." In particular, the enhancement of childcare policies and improvements to housing and infrastructure were found to play a central role in creating a birth-friendly society. The findings also highlight the importance of socio-cultural changes through the promotion of gender equality and labor environment improvements.

Second, the core causal structures identified were expressed and analyzed using causal loop diagrams in

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the system dynamics framework. The analysis revealed three reinforcing feedback loops and three balancing feedback loops. The reinforcing loops—Gender Equality Promotion, Childcare Environment Improvement, and Education–Perception Improvement—demonstrate a structure in which the enhancement of gender equality, improvements in childcare environments, and shifts in public perception about childbirth and family formation mutually reinforce one another, sustaining positive effects in addressing the low birthrate issue over the long term. In contrast, the balancing loops—Social Burden, Labor Environment, and Economic Burden and Fertility Intention—illustrate self-regulating mechanisms that respond to negative pressures such as increasing social burdens or worsening labor conditions by prompting counteracting societal responses.

Third, based on the analysis of these feedback loops, the government should prioritize the following policy directions to fundamentally resolve the low birthrate crisis.

1. First, the government should actively improve living infrastructure centered around childcare policies to minimize the economic and social burden of raising children.
2. Second, gender equality and work–life balance policies should be strengthened, and structural imbalances in the labor market should be addressed to ensure childbirth and parenting can be freely chosen.
3. Third, education programs and awareness campaigns should be promoted to improve social perceptions of the low birthrate issue and foster a birth-friendly culture.
4. Lastly, a responsive and flexible policy framework should be established to manage rising social burdens associated with fertility decline and prevent the issue from worsening.

In conclusion, this study holds significant value in that it systematically analyzed the complexity of the low birthrate phenomenon by integrating big data analysis with system dynamics modeling. Going forward, it is expected that the government and policymakers can utilize this structural and integrated approach to design and implement more refined and effective low birthrate policies.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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