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Mathematical Taxonomy of Health Insurance Models: Conventional Approaches and the Emergent C&C Paradigm

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Mathematical Taxonomy of Health Insurance Models: Conventional Approaches and the Emergent C&C Paradigm

Abstract

Health insurance systems worldwide face unprecedented sustainability challenges due to demographic transitions and financial pressures. Despite extensive comparative policy literature, there remains a notable gap in formal mathematical representation of how different insurance models function under stress conditions. This paper develops a comprehensive mathematical taxonomy of four principal health insurance models: the Bismarckian model (employment-based social insurance), the Beveridgean model (tax-funded universal coverage), the Commercial model (risk-based private insurance), and the Collaborative & Contributive (C&C) model (communitybased governance with trust-based sustainability). We establish formal mathematical representations of each model's core structures, develop equilibrium conditions defining sustainability requirements, and create a comparative framework identifying distinctive properties across models. Our analysis reveals that each model constitutes a fundamentally distinct insurance paradigm with unique mathematical properties affecting its resilience to demographic and financial pressures. The C&C model, which uniquely incorporates trust as an explicit mathematical variable, demonstrates distinctive properties in terms of sustainability thresholds and value proposition expansion. This mathematical taxonomy enables more precise identification of critical vulnerabilities and potential innovation pathways in health insurance system design. (174)

Keywords

Health insurance models; Mathematical modeling; Bismarckian system; Beveridgean system; Commercial insurance; Collaborative and Contributive (C&C) model; Trust dynamics;

Demographic resilience; System equilibrium; Risk pooling; Sustainability thresholds; Mathematical taxonomy; Healthcare financing

Highlights

- Establishes formal mathematical representations for four distinct health insurance models
- Develops precise equilibrium conditions and sustainability thresholds for each system
- Demonstrates differential mathematical responses to demographic and financial pressures
- Identifies trust as a unique mathematical variable in the C&C model with implications for system resilience
- Creates a rigorous comparative framework for analyzing health insurance system vulnerabilities

1. Introduction

Health insurance systems worldwide face unprecedented challenges from demographic transitions and financial pressures. Population aging in developed economies and demographic dividends in emerging markets create distinct sustainability challenges that demand rigorous analysis. Despite extensive comparative policy literature on health systems (Kutzin, 2001; Normand & Busse, 2002; Wagstaff, 2009), there remains a notable gap in formal mathematical representation of how different insurance models function, particularly under stress conditions.

This paper addresses this gap by developing a comprehensive mathematical taxonomy of four principal health insurance models: the Bismarckian model (employment-based social insurance), the Beveridgean model (tax-funded universal coverage), the Commercial model (risk-based private insurance), and the Collaborative & Contributive (C&C) model (community-based governance with trust-based sustainability). While qualitative comparisons of these systems are

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common (Saltman et al., 2004; Van der Zee & Kroneman, 2007), systematic mathematical frameworks that enable rigorous comparison remain underdeveloped. Recent work by Rice et al. (2023) has applied machine learning techniques to revisit traditional Bismarck and Beveridge classifications, further highlighting the need for more sophisticated analytical frameworks that can capture the structural differences between health insurance systems.

Our approach integrates concepts from health policy, insurance economics, and mathematical modeling to create a comprehensive framework. For each system, we identify core parameters and variables that represent distinctive structural features, including demographic factors, economic variables, and system-specific parameters. By formalizing these elements, we create a mathematical taxonomy that enables direct comparison of fundamental properties across systems, moving beyond descriptive policy analysis to identify structural similarities and differences with mathematical precision.

The objectives of this paper are threefold:

- 1. To establish formal mathematical representations of each insurance model's core structures and operating principles.
- 2. To develop equilibrium conditions and formal propositions that define sustainability requirements for each system.
- 3. To create a comparative framework that identifies distinctive mathematical properties and vulnerabilities across the four models.

2. Literature Review and Conceptual Framework

The comparative analysis of health systems has evolved from descriptive typologies to more sophisticated frameworks examining financing mechanisms, service provision, and governance structures. Field (1973) pioneered a macrosociological framework, while Roemer (1991) developed a comprehensive classification system. More recent frameworks by Murray & Frenk (2000) and Wendt et al. (2009) have distinguished between Bismarckian, Beveridgean, and mixed system types, with Fan et al. (2021) demonstrating through modeling how investment in different health system structures yields varying returns for economic growth and population health.

While these comparative analyses provide valuable policy insights, they often lack mathematical precision. Arrow (1963) established that health insurance markets have distinctive economic properties that benefit from formal mathematical treatment. Cutler and Zeckhauser (2000) extended this tradition by developing mathematical models of risk selection and market equilibrium, though primarily focused on private insurance markets rather than system-level analysis.

Mathematical modeling in health insurance has primarily focused on actuarial aspects of risk pooling, optimal contract design, and risk adjustment mechanisms. Bowers et al. (1997) established foundational work on actuarial mathematics, while Van de Ven & Ellis (2000) developed mathematical frameworks for risk adjustment mechanisms in competitive markets. More recently, Decarolis et al. (2020) advanced the mathematical modeling of subsidy design in privately provided social insurance, demonstrating how incentive structures affect market outcomes, while Tebaldi (2022) developed equilibrium models for health insurance exchanges that incorporate price competition and subsidy design

The concept of microinsurance emerged as an approach to extend insurance to populations excluded from conventional systems. Dror and Jacquier (1999) introduced the term "micro-insurance" to describe community-based risk-pooling schemes designed for low-income populations. More recently, Dror (2023) has articulated the distinctive characteristics of what he

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terms the Collaborative and Contributive (C&C) model, emphasizing voluntary participation, community-led governance, and trust-based sustainability.

Building on these theoretical foundations, we define a health insurance system mathematically as a set of functions and equilibrium conditions that determine: (1) revenue generation mechanisms, (2) risk pooling structures, (3) benefit determination processes, and (4) sustainability constraints.

3. General Mathematical Framework for Health Insurance Systems

3.1 Core System Variables and Parameters

We denote time with variable \$t\$ and define the following general variables and parameters:

- \$N(t)\$: Total population at time \$t\$
- \$D(t)\$: Demographic dependency ratio at time \$t\$
- \$TC(t)\$: Total system contributions/revenues at time \$t\$
- \$TB(t)\$: Total system benefits/expenditures at time \$t\$
- \$A(t)\$: Administrative costs at time \$t\$
- \$R(t)\$: Risk adjustment factor at time \$t\$

The population can be segmented into relevant subgroups:

- \$N_w(t)\$: Working/contributing population
- \$N_d(t)\$: Dependent/non-contributing population

The demographic dependency ratio is then defined as:

 $\label{eq:1} equation D(t) = \frac{N_w(t)}{N_d(t)} \label{eq:1} \equation}$

This ratio is a critical parameter for analyzing health insurance system sustainability, as it relates

the revenue-generating population to the dependent population.

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3.2 General Equilibrium Condition

All sustainable health insurance systems must satisfy a basic equilibrium condition: revenues must be sufficient to cover expenditures over time. Formally:

 $\left(equation\right) TC(t) \left(eq TB(t) + A(t) \right) + A(t) \left(eq(t) + A(t) \right) + A(t) \right)$

This general constraint applies across all systems, though the specific mechanisms for ensuring this equilibrium vary substantially between models.

3.3 System Sustainability Function

We define a system sustainability function S(t) as:

 $\left(equation\right) S(t) = TC(t) - TB(t) - A(t) \left(equation\right)$

For a system to remain sustainable, $S(t) \ge 0$ must hold. The behavior of S(t) under varying demographic and financial conditions differs markedly across systems.

3.4 Demographic and Financial Sensitivity

The sensitivity of system sustainability to demographic change can be formally expressed as the partial derivative:

\begin{equation} \frac{\partial S(t)}{\partial D(t)} \label{eq:4} \end{equation}

Similarly, sensitivity to financial pressures (such as economic downturns or healthcare inflation) can be expressed as:

\begin{equation} \frac{\partial S(t)}{\partial F(t)} \label{eq:5} \end{equation}

Where \$F(t)\$ represents relevant financial pressure indicators.

3.5 Risk Pooling Mechanisms

Copyright © 2025 David M. Dror This work is licensed under the Creative Commons Attribution 4.0 International License (CC BY 4.0). To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/ Each health insurance system incorporates some form of risk pooling, though the mathematical structure varies significantly. We define a general risk pooling function \$RP(t)\$ that determines how financial risks are distributed across the insured population:

 $\begin{equation} RP(t) = f(N(t), R(t), TC(t), TB(t)) \label{eq:6} \equation \$

3.6 Benefit Calculation Function

The expected benefits for an individual \$i\$ can be generally expressed as:

 $\label{eq:7} equation B_i(t) = \sum_{s \in S} p_s(t) \times c_s \times u_{i,s}(t) \times r_s(t) \label{eq:7} \equation \label{eq:7} \la$

Where:

- p_s(t): Probability of needing service s at time t
- c_s: Cost of service s
- u_{i,s}(t): Utilization rate of service \$s\$ by individual i at time t
- r_s(t): Reimbursement/coverage rate for service s at time t

4. Mathematical Model of the Bismarckian System

4.1 Model Structure and Core Assumptions

The Bismarckian model operates under these key assumptions:

- 1. Contributions are mandatory for employed individuals and proportional to income
- 2. Employers and employees typically share contribution costs
- 3. Coverage extends to dependents of contributing members

- 4. Benefits are standardized across the insured population
- 5. Multiple insurance funds may exist but operate under common regulations

4.2 Revenue Generation Mechanism

In the Bismarckian model, revenues primarily derive from income-based contributions shared between employers and employees. Total contributions can be expressed as:

 $\label{eq:alpha} $$ TC_B(t) = \left[\sum_{i=1}^{n} {C_e(t) \setminus dot I_i(t) + C_w(t) \setminus dot I_i(t)} \right] \ R_B(t) \setminus \left[eq:8\right] \ equation $$ Tc_B(t) \setminus \left[eq:8\right] \ equation $$ Tc_B(t) \cap \left[eq:8\] \ equation $$ Tc_B$

Where:

- \$C_e(t)\$: Employer contribution rate at time \$t\$
- \$C_w(t)\$: Worker contribution rate at time \$t\$
- \$I_i(t)\$: Income of individual \$i\$ at time \$t\$
- \$I_i(t)\$: Income of individual \$i\$ at time \$t\$
- \$R_B(t)\$: Risk adjustment factor specific to Bismarckian systems

4.3 Individual Premium Calculation

For an individual in a Bismarckian system, the premium or contribution is calculated as:

 $\left(equation\right) P_i(t) = [C_e(t) + C_w(t)] \quad I_i(t) \quad equation$

This creates a direct proportionality between income and contributions, establishing income solidarity within the system.

4.4 Equilibrium Condition

Copyright © 2025 David M. Dror This work is licensed under the Creative Commons Attribution 4.0 International License (CC BY 4.0). To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/ The equilibrium condition requires contributions to cover benefits and administrative costs:

\begin{equation}

 $\sum_{i=1}^{n} P_i(t) \ge \sum_{i=1}^{n} B_i(t) + A_B(t)$

 $label{eq:10}$

\end{equation}

Where \$A_B(t)\$ represents administrative costs specific to the Bismarckian system at time \$t\$.

4.5 Demographic Sensitivity

The sensitivity of the Bismarckian system to demographic changes can be analyzed by examining the derivative of contribution rates with respect to the dependency ratio:

\begin{equation}

 $\frac{dC_w(t)}{dD(t)} = -\frac{A_B(t)}{2 \det I_{average}(t)}$

```
\det n \det R_B(t) \det D(t)^2
```

 $label{eq:11}$

\end{equation}

This negative relationship indicates that as the dependency ratio decreases (fewer workers relative to dependents), contribution rates must increase non-linearly to maintain system equilibrium.

4.6 Distinctive Mathematical Features

The Bismarckian model exhibits several mathematically distinctive features:

- Income-Based Risk Pooling: Risk is pooled across income levels, with contributions directly proportional to income.
- Employment Dependency: System sustainability is mathematically linked to employment levels and the wage share of the economy.
- 3. **Non-Linear Demographic Sensitivity**: Contribution rates respond non-linearly to changes in the demographic dependency ratio.
- 4. Actuarial Indifference to Individual Risk: Individual premiums are calculated independent of individual risk factors, creating a mathematical separation between financing and risk.

5. Mathematical Model of the Beveridgean System

5.1 Model Structure and Core Assumptions

The Beveridgean model operates under these key assumptions:

- 1. Healthcare is financed primarily through general taxation
- 2. Coverage is universal and independent of employment status
- 3. Service provision is predominantly through public facilities or contracted providers
- 4. Resource allocation is determined through budgetary processes
- 5. Access to services may be managed through waiting lists and prioritization systems

5.2 Revenue Generation Mechanism

In Beveridgean systems, revenues derive primarily from general taxation, with healthcare allocation determined through budgetary processes:

\begin{equation}

 $TC_V(t) = \label{eq:vector} V(t) = \label{eq$

 $times I_i(t)$

 $label{eq:12}$

\end{equation}

Where:

- \$\alpha(t)\$: Proportion of tax revenue allocated to healthcare at time \$t\$
- \$\tau(I_i(t))\$: Progressive tax rate function applied to income of individual \$i\$
- \$I_i(t)\$: Income of individual \$i\$ at time \$t\$

5.3 Budget Allocation Process

The total healthcare budget is allocated across services and regions according to need-based formulas:

\begin{equation}

 $HC_j(t) = HC(t) \setminus frac \{ N_j(t) \setminus times \}$

 $AF_j(t) \{ \sum_{k=1}^{r} N_k(t) \in AF_k(t) \}$

 $label{eq:13}$

\end{equation}

Where:

- \$HC_j(t)\$: Healthcare budget for region \$j\$ at time \$t\$
- \$N_j(t)\$: Population in region \$j\$ at time \$t\$
- \$AF_j(t)\$: Adjustment factor for region \$j\$ based on demographic and health need indicators
- \$r\$: Total number of regions

5.4 Service Rationing Mechanism

A distinctive mathematical feature of Beveridgean systems is the service rationing function, which adjusts service availability based on budget constraints:

\begin{equation}

 $v_s(t) = f \left(\frac{HC(t)}{D(t)}, p_s(t) \right)$

 $label{eq:14}$

\end{equation}

Where:

- \$v_s(t)\$: Access factor for service \$s\$ at time \$t\$ (accounting for waiting times/rationing)
- \$HC(t)\$: Healthcare allocation at time \$t\$
- \$p_s(t)\$: Population-level need for service \$s\$

The access factor influences actual service utilization:

\begin{equation}

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 $u_{i,s}(t) = u_{i,s}^{*}(t) \setminus times v_{s}(t)$

 $label{eq:15}$

\end{equation}

Where $u_{i,s}^{*}(t)$ represents the idealized utilization without access constraints.

5.5 Equilibrium Condition

The fundamental equilibrium condition for Beveridgean systems is that healthcare expenditure cannot exceed the allocated budget:

\begin{equation}

 $\sum_{i=1}^{n} \sum_{s \in S} p_s(t) \le c_s \le c_s$

 $u_{i,s}(t) \to v_s(t) + A_V(t) = HC(t)$

 $label{eq:16}$

 $end{equation}$

Where $A_V(t)$ represents administrative costs specific to the Beveridgean system at time t.

5.6 Demographic Sensitivity

The sensitivity of service access to demographic changes can be expressed as:

\begin{equation}

 $\frac{v_s(t)}{\partial t} = \frac{v_s(t)}{\partial t}$

 v_s {\partial(HC(t)/D(t))} \times \frac{-HC(t)}{D(t)^2}

 $label{eq:17}$

\end{equation}

This demonstrates how service access must contract as the demographic dependency ratio decreases (aging population), assuming a constant budget allocation.

5.7 Distinctive Mathematical Features

- 1. **Budget-Constrained Service Provision**: Unlike premium-based systems, Beveridgean systems adjust service access rather than revenue levels when facing financial pressures.
- Progressive Financing Structure: The progressive tax function creates a different revenue pattern than proportional Bismarckian contributions or risk-based commercial premiums.
- 3. Universal Coverage Independent of Contributions: The mathematical decoupling of coverage eligibility from individual contributions creates a distinct risk pooling structure.
- 4. **Service Rationing as Equilibrium Mechanism**: The access factor serves as the primary mathematical mechanism for maintaining financial equilibrium under resource constraints.

6. Mathematical Model of the Commercial Health Insurance System

6.1 Model Structure and Core Assumptions

The Commercial model operates under these key assumptions:

- 1. Premiums are calculated based on individual or group risk factors
- 2. Participation is typically voluntary

- 3. Insurers operate as profit-maximizing entities
- 4. Market competition influences premium levels and benefit design
- 5. Regulation constrains underwriting and pricing practices to varying degrees

The Commercial model represents insurance as a market-based mechanism operating under competitive pressures. Recent work by Einav et al. (2022) demonstrates how market failures emerge in exchange-based healthcare systems, providing empirical support for the mathematical vulnerabilities we identify in the Commercial model. These market imperfections fundamentally affect the equilibrium conditions that we model below.

6.2 Revenue Generation Mechanism

In Commercial health insurance systems, revenues derive from risk-adjusted premiums that vary by individual characteristics:

\begin{equation}

 $TC_{COM}(t) = \sum_{i=1}^{n} P_i(t) \det \det_i(t)$

 $label{eq:18}$

\end{equation}

Where:

- \$TC_{COM}(t)\$: Total contributions/revenues at time \$t\$
- \$P_i(t)\$: Premium charged to individual \$i\$ at time \$t\$
- $delta_i(t)$: Indicator function for enrollment ($delta_i(t) = 1$ if enrolled, 0 otherwise)

The premium for individual \$i\$ is calculated as:

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\begin{equation}

 $P_i(t) = E[M_i(t)] \ (1 + \ (1 + \ (COM)(t)) \ (1 + \ (1 + \ (M_i(t)) \ (M_i(t))) \ (M_i(t)) \ (M$

pi(t)

 $label{eq:19}$

 $end{equation}$

Where:

- \$E[M_i(t)]\$: Expected medical costs for individual \$i\$ at time \$t\$
- \$\lambda_{COM}(t)\$: Loading factor for administrative costs
- \$\pi(t)\$: Profit margin at time \$t\$

The expected medical costs are estimated based on observable risk factors:

\begin{equation}

 $E[M_i(t)] = \frac{0(t) + \sum_{j=1}^{k} \frac{b_{j,j}}{k}$

 $X_{ij}(t)$

 $\label{eq:20}$

\end{equation}

Where:

- \$\beta_0(t)\$: Baseline expected cost at time \$t\$
- \$\beta_j(t)\$: Risk coefficient for factor \$j\$ at time \$t\$

\$X_{ij}(t)\$: Value of risk factor \$j\$ for individual \$i\$ at time \$t\$ (age, gender, health status, etc.)

6.3 Enrollment Decision Model

An individual's decision to enroll in a commercial plan depends on the premium relative to their willingness to pay:

\begin{equation}

 $\det_i(t) = e_i(t)$

1 & $text{if } P_i(t) \leq WTP_i(t)$

0 & \text{otherwise}

 \end{cases}

 $label{eq:21}$

\end{equation}

Where \$WTP_i(t)\$ represents individual \$i\$'s willingness to pay for health insurance at time \$t\$.

The relationship between financial constraints and insurance decisions affects equilibrium outcomes in commercial systems. Célerier and Vallée (2023) demonstrate how saving constraints intersect with health insurance design, affecting participation decisions in ways that our mathematical models must account for. These constraints influence the willingness-to-pay function in equation (21) and consequently affect system equilibrium.

6.4 Profit Maximization Objective

Commercial insurers operate with a profit maximization objective:

\begin{equation}

 $\max Pi(t) = TC_{COM}(t) - TB_{COM}(t) - A_{COM}(t)$

 $label{eq:22}$

 $end{equation}$

Where:

- \$\Pi(t)\$: Profit at time \$t\$
- \$TB_{COM}(t)\$: Total benefit payments at time \$t\$
- \$A_{COM}(t)\$: Administrative costs at time \$t\$

6.5 Equilibrium Condition

The equilibrium condition for commercial systems requires that total premium revenue exceeds expected claims plus administrative costs and target profit:

\begin{equation}

 $\sum_{i=1}^{n} \det_i(t) \det P_i(t) \operatorname{geq} \sum_{i=1}^{n}$

 $\det_i(t) \subset E[M_i(t)] + A_{COM}(t) + Pi_{target}(t)$

 $label{eq:23}$

\end{equation}

6.6 Demographic Sensitivity Analysis

The effect of demographic aging on commercial premiums can be expressed as:

\begin{equation}

 $\frac{12}{E[M_i(t)]}{\text{ partial age}^2} > 0$

 $label{eq:24}$

\end{equation}

This indicates that premiums increase with age, and at an accelerating rate.

6.7 Adverse Selection Dynamics

A distinctive feature of commercial systems is the potential for adverse selection, where higherrisk individuals are more likely to enroll at given premium levels:

\begin{equation}

 $\frac{\phi_i(t)}{\phi_i(t)} > 0$

 $label{eq:25}$

 $end{equation}$

This dynamic can lead to premium spirals in which:

\begin{equation}

 $\frac{dP(t)}{dt} = \frac{\sqrt{t}}{t}$

 $\label{eq:entropy_frac} \\ E[M_i(t) | \\ delta_i(t) = 1] \\ E[M_i(t)] \\ -1 \\$

\right)

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 $label{eq:26}$

\end{equation}

Where $\operatorname{E}[M_i(t) | \det_i(t) = 1]$ is the average expected cost of those who choose to enroll.

6.8 Distinctive Mathematical Features

- 1. **Risk-Based Pricing**: Premiums are mathematically linked to individual risk factors, creating a fundamentally different revenue structure than community-rated or income-based systems.
- 2. **Profit Maximization Objective**: The explicit inclusion of a profit term in the objective function creates distinct incentives absent in non-profit models.
- 3. **Risk Selection Mechanisms**: Commercial systems include mathematical functions for risk classification and selection that optimize the risk pool.
- 4. **Market Competition Effects**: Premium setting includes competitive market dynamics that constrain pricing through mathematical relationships.
- 5. Adverse Selection Vulnerability: The voluntary nature of participation creates mathematical dynamics absent in mandatory systems.

7. Mathematical Model of the C&C (Collaborative & Contributive) System

7.1 Model Structure and Core Assumptions

The C&C model operates under these key assumptions:

1. Participation is voluntary and based on mutual agreement

- 2. Governance is community-based rather than market-driven or state-controlled
- 3. Premiums are community-rated rather than risk-rated or income-proportional
- 4. Trust dynamics play a central role in system sustainability
- 5. Benefit packages reflect community preferences rather than external standards

7.2 Revenue Generation Mechanism

In the C&C model, contributions are based on community-rated premiums and voluntary participation:

\begin{equation}

 $TC_C(t) = N(t) \setminus times P(t) \setminus times TR(t)$

 $label{eq:27}$

\end{equation}

Where:

- \$N(t)\$: Number of participants at time \$t\$
- \$P(t)\$: Community-rated premium at time \$t\$
- TR(t): Trust factor affecting participation rate $(0 < TR(t) \setminus [0])$

The premium is determined based on expected benefit payments and loading factors, with trust explicitly incorporated as a mathematical variable:

\begin{equation}

 $P(t) = \frac{B(t) \times (1 + \operatorname{lambda}(t))}{N(t) \times (R(t))}$

 $label{eq:28}$

\end{equation}

Where:

- \$B(t)\$: Expected benefit payouts
- \$\lambda(t)\$: Loading factor

This creates a direct mathematical relationship between trust and premium levels that is absent in other models.

7.3 Trust Factor Dynamics

A distinctive mathematical feature of the C&C model is the trust factor, which evolves based on community experience:

\begin{equation}

 $TR(t+1) = TR(t) + \det times [CS(t) - TR(t)]$

 $label{eq:29}$

\end{equation}

Where:

- \$CS(t)\$: Claim settlement satisfaction at time \$t\$ \$(0 \leq CS(t) \leq 1)\$
- $\$ delta: Learning adjustment rate $(0 < \ (0 < \ (1)))$

This represents a learning process where trust adjusts based on the gap between current trust and actual experience with claim settlements.

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7.4 Participation Dynamics

The number of participants evolves based on trust and premium affordability:

\begin{equation}

 $N(t+1) = N(t) \text{ times } [1 + g_N(TR(t), P(t), W(t))]$

 $label{eq:30}$

\end{equation}

Where:

- \$g_N\$: Growth function for participation
- \$W(t)\$: Average willingness to pay at time \$t\$

The growth function can be specified as:

\begin{equation}

 $g_N(TR(t), P(t), W(t)) = \alpha_1 \times TR(t) - \alpha_2 \times$

 $\frac{P(t)}{W(t)} + \frac{B(t)}{2}$

 $label{eq:31}$

 $end{equation}$

With $\lambda_1, \lambda_2, \lambda_3$ as sensitivity parameters.

7.5 Benefit Structure

Benefits in the C&C model are community-determined, with coverage reflecting local priorities:

\begin{equation}

 $B_i(t) = \sum \{s \in S_c\} p_s(t) \in c_s \in u_{i,s}(t)$

 $times d_s(t)$

 $\label{eq:32}$

\end{equation}

Where:

- \$S_c\$: Community-determined set of covered services
- \$d_s(t)\$: Community demand factor for service \$s\$

Unlike conventional models where benefit packages are determined through regulatory or corporate processes, the C&C model evolves benefits through community decision processes:

\begin{equation}

 $S_c(t+1) = g(S_c(t), TR(t), N(t), P(t))$

 $\label{eq:33}$

 $end{equation}$

This creates a direct mathematical relationship between member preferences and covered services.

7.6 Equilibrium Condition

The equilibrium condition for the C&C model includes trust dynamics:

\begin{equation}

Copyright © 2025 David M. Dror This work is licensed under the Creative Commons Attribution 4.0 International License (CC BY 4.0). To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/ $N(t) \setminus B(t) \setminus B(t) \setminus B(t) + A_C(t)$

 $label{eq:34}$

 $end{equation}$

Where \$A_C(t)\$ represents administrative costs specific to the C&C model at time \$t\$.

This can be rewritten as a constraint on the minimum required trust level:

\begin{equation}

 $TR(t) \left| geq \left| frac \{B(t) + A_C(t)\} \{N(t) \mid times P(t)\} \right|$

 $label{eq:35}$

 $end{equation}$

7.7 Demographic Sensitivity

The C&C model's response to demographic pressure operates through the trust-premium relationship:

\begin{equation}

 $\frac{P(t)}{\mathbb{D}(t)} = \frac{P(t)}{\tau}$

D(t) \left(\frac{B(t) \times (1 + \lambda(t))}{N(t) \times

TR(t)

 $\label{eq:36}$

 $end{equation}$

If trust positively correlates with the dependency ratio (as the elderly often have higher social capital in communities), then:

\begin{equation}

 $\frac{D(t)}{0} > 0$

 $label{eq:37}$

 $end{equation}$

This creates a potential buffering effect against demographic pressure.

7.8 Premium Calculation Distinctiveness

A distinctive feature of the C&C model is its unique premium calculation mechanism:

\begin{equation}

 $\frac{P(t)}{\operatorname{P}(t)} = -\frac{B(t)}{\operatorname{P}(t)} = -\frac{B(t)}{\operatorname{P}(t)}$

```
\lambda(t) \in TR(t)^2 < 0
```

 $\label{eq:38}$

\end{equation}

This equation demonstrates a critical property absent in all other insurance models: as trust increases, premiums can decrease while maintaining the same level of benefits.

7.9 Value Proposition Expansion

The C&C model demonstrates a mathematical expansion of the value proposition beyond mere risk protection:

\begin{equation}

 $V_C(t) = V_{\text{risk}}(t) + V_{\text{pref}}(t) + V_{\text{social}}(t)$

 $label{eq:39}$

 $end{equation}$

Where:

- \$V_{risk}(t)\$: Value from risk protection
- \$V_{pref}(t)\$: Value from preference alignment
- \$V_{social}(t)\$: Value from social capital formation

This multi-dimensional value function distinguishes the C&C model from conventional approaches where:

\begin{equation}

 $V_{conv}(t) = V_{risk}(t)$

 $\label{eq:40}$

\end{equation}

7.10 Distinctive Mathematical Features

1. **Trust as a Mathematical Variable**: The explicit inclusion of trust as a quantifiable parameter in premium calculations introduces a dimension absent in other models.

- Participation-Premium Feedback Loop: The mathematical relationship between trust, participation rates, and premium levels creates a distinctive positive feedback mechanism not present in other systems.
- 3. **Community Preference Alignment**: The direct mathematical relationship between community preferences and benefit structure allows for adaptation to local needs.
- 4. **Multi-Dimensional Value Function**: The expansion of the value proposition beyond risk protection to include preference alignment and social capital formation creates a fundamentally different utility function.
- 5. **Trust-Based Sustainability Mechanism**: The model's equilibrium condition explicitly incorporates trust, creating a distinct sustainability mechanism that operates through social rather than purely financial variables.

8. Formal Mathematical Propositions and Proofs

This section presents the key mathematical propositions that emerge from our comparative analysis of health insurance models, along with their formal proofs.

8.1 Proposition 1: Bismarckian Demographic Sensitivity

Proposition 1: Under demographic pressure (decreasing \$D(t)\$), contribution rates in Bismarckian systems must increase non-linearly according to:

\begin{equation}

 $\label{eq:constraint} $$ \int dC_w(t) dD(t) = -\frac{A_B(t)}{2 \ cdot \ I_{average}(t) \ cdot \ n \ cdot \ R_B(t) \ cdot \ D(t)^2 < 0 $$$

 $label{eq:85}$

\end{equation}

Proof:

The equilibrium condition for a Bismarckian system requires:

\begin{equation}

 $TC_B(t) \setminus geq TB_B(t) + A_B(t)$

 $label{eq:86}$

 $end{equation}$

Where total contributions are:

\begin{equation}

 $TC_B(t) = \sum_{i=1}^{n} [C_e(t) + C_w(t)] \det I_i(t) \det R_B(t)$

 $\label{eq:87}$

 $end{equation}$

For simplicity, we assume $C_e(t) = C_w(t)$ and approximate $\sum_{i=1}^{n} I_i(t) \ge n$

 $\quad I_{average}(t)$, where $n\$ is the number of contributors.

At equilibrium:

\begin{equation}

 $2 \det C_w(t) \det n \det I_{average}(t) \det R_B(t) = TB_B(t) + A_B(t)$

 $label{eq:88}$

 $end{equation}$

Solving for \$C_w(t)\$:

\begin{equation}

 $C_w(t) = \frac{TB_B(t) + A_B(t)}{2 \det n \det I_{average}(t) \det R_B(t)}$

 $label{eq:89}$

\end{equation}

The demographic dependency ratio $D(t) = \frac{N_w(t)}{N_d(t)}$ affects total benefit expenditure $TB_B(t)$, which can be expressed as:

\begin{equation}

 $TB_B(t) = TB_w(t) + TB_d(t) = b_w \setminus cdot N_w(t) + b_d \setminus cdot N_d(t)$

 $label{eq:90}$

\end{equation}

Where b_w and b_d are the average benefits per worker and dependent, respectively.

Substituting into the equation for \$C_w(t)\$:

\begin{equation}

 $C_w(t) = \frac{b_w \cdot dt N_w(t) + b_d \cdot dt N_d(t) + A_B(t)}{2 \cdot dt I_{average}(t)}$

 $\label{eq:91} \\$

\end{equation}

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Since $N_w(t) = D(t) \setminus O(t)$ and $n \geq N_w(t)$:

\begin{equation}

 $C_w(t) = \frac{b_w \det D(t) \det N_d(t) + b_d \det N_d(t) + A_B(t)}{2 \det D(t) \det D(t)}$

 $N_d(t) \setminus dot I_{average}(t) \setminus dot R_B(t)$

 $label{eq:92}$

 $end{equation}$

Simplifying:

\begin{equation}

 $C_w(t) = \frac{b_w \det D(t) + b_d + \frac{A_B(t)}{N_d(t)}}{2 \det D(t) \det I_{average}(t)}$

\label{eq:93}

\end{equation}

Taking the derivative with respect to \$D(t)\$:

\begin{equation}

 $\label{eq:control} $$ dD(t) = \frac{2 \quad 0 \quad D(t) \quad dt \quad A_B(t) \quad b_w - b_w - b_w \quad cdot \quad D(t) + b_d + \frac{A_B(t)}{N_d(t)} \quad cdot \quad A_B(t) \quad cdot$

 $label{eq:94}$

\end{equation}

Simplifying:

\begin{equation}

 $\label{eq:linear} $$ \frac{dC_w(t)}{dD(t)} = -\frac{b_d + \frac{A_B(t)}{N_d(t)}}{2 \quad \text{(average)}(t) \quad \text{(dot } R_B(t) \quad 0 \quad t^2} $$$

 $label{eq:95}$

 $end{equation}$

If we focus on the administrative cost component, which is relatively independent of demographic changes in the short term:

\begin{equation}

 $\label{eq:linear} $$ \int dC_w(t) dD(t) = -\int (A_B(t)) dD(t) = -\int (A_B(t)) dD(t) dD(t) = -\int (A_B(t)) dD(t) dD($

 $label{eq:96}$

\end{equation}

This proves that contribution rates must increase non-linearly (as an inverse square function) as the dependency ratio decreases.

Implication: Bismarckian systems face accelerating sustainability challenges as populations age, requiring contribution rates to increase at an increasing rate to maintain system equilibrium.

8.2 Proposition 2: Beveridgean Service Access Sensitivity

Proposition 2: Service access (\$v_s(t)\$) in Beveridgean systems contracts as a function of decreasing demographic ratio according to:

32

\begin{equation}

```
\label{eq:partial v_s(t)} $$ \ D(t) = \ C(t) \ U(t) \ times \ \ e^{-t} \ D(t)^{2} > 0 $$ \ C(t)^{2} > 0 $$ \ C(t)^{2}
```

 $label{eq:97}$

 $end{equation}$

Proof:

The equilibrium condition for a Beveridgean system is:

\begin{equation}

 $\label{eq:sum_in_s} sum_{i=1}^{n} sum_{s \in S} p_s(t) times c_s times u_{i,s}(t) times v_s(t) + A_V(t) leq HC(t)$

 $\label{eq:98}$

 $end{equation}$

Where $v_s(t)$ is the access factor for service s, which is a function of the per-capita healthcare budget:

\begin{equation}

 $v_s(t) = f \left(\frac{HC(t)}{N(t)}, p_s(t) \right)$

 $\label{eq:99}$

 $end{equation}$

Since $N(t) = N_w(t) + N_d(t)$ and $D(t) = \frac{N_w(t)}{N_d(t)}$, we can express N(t) in terms of D(t):

\begin{equation}

 $N(t) = N_d(t) + N_w(t) = N_d(t) + D(t) \setminus cdot N_d(t) = N_d(t) \setminus cdot (1 + D(t))$

 $label{eq:100}$

 $end{equation}$

Therefore:

\begin{equation}

 $v_s(t) = f \left(\frac{HC(t)}{N_d(t) \cdot d(t)}, p_s(t) \right)$

 $label{eq:101}$

 $end{equation}$

For simplicity, let $\frac{HC(t)}{N_d(t)} = HC'(t)$, so:

\begin{equation}

 $v_s(t) = f \left(\frac{HC'(t)}{1 + D(t)}, p_s(t) \right)$

 $label{eq:102}$

 $end{equation}$

Taking the partial derivative with respect to \$D(t)\$:

\begin{equation}

 $\label{eq:linear} $$ \frac{\sigma_s(t)}{\sigma_t(t)} = \frac{\sigma_s}{\rho_t(t)} + D(t) \frac{D(t)}{\tau_s(t)} \\ \\ \frac$

 $label{eq:103}$

 $end{equation}$

Computing the second term:

\begin{equation}

 $frac{\operatorname{D}(t)} (frac{HC'(t)}{1 + D(t)} right) = frac{-HC'(t)}{(1 + D(t))^2}$

 $label{eq:104}$

\end{equation}

Since $\frac{\left(\frac{v_s}{(t)}\right)}{0} > 0\$ (access increases with per-capita budget), and $\frac{-HC'(t)}{(1 + D(t))^2} < 0\$, we have:

\begin{equation}

 $\label{eq:linear} $$ \frac{\sigma_s(t)}{\sigma_t(t)} = \frac{\sigma_s}{\rho_t(t)} + D(t) \frac{1 + D(t)}{\tau_s} = \frac{1 + D(t)}{1 + D(t)} = 0$

 $label{eq:105}$

\end{equation}

Expressing this in terms of the original healthcare budget:

\begin{equation}

 $label{eq:106}$

 $end{equation}$

This proves that service access contracts as the demographic ratio decreases.

Implication: Beveridgean systems respond to demographic pressure through service rationing rather than revenue increases, leading to decreased access to services as populations age.

8.3 Proposition 3: Commercial Risk Segmentation and Premium Growth

Proposition 3: Commercial health insurance systems exhibit premium growth that is both positive and accelerating with respect to age:

\begin{equation}

 $\frac{1}{2} > 0 \quad \text{frac} P_i(t)$

 $label{eq:107}$

\end{equation}

Proof:

From the premium equation and expected cost function:

\begin{equation}

 $P_i(t) = E[M_i(t)] \ (1 + \ (1 + \ (t))) \ (t) \ (1 + \ (t)))$

 $label{eq:108}$

Copyright © 2025 David M. Dror This work is licensed under the Creative Commons Attribution 4.0 International License (CC BY 4.0). To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/ $end{equation}$

\begin{equation}

 $E[M_i(t)] = \frac{0(t) + \sum_{j=1}^{k} (k) \sum_{j=1}$

 $label{eq:109}$

 $end{equation}$

Let $X_{i1}(t) = age_i$ and assume $beta_1(t) > 0$ (medical costs increase with age).

Taking the partial derivative with respect to age:

\begin{equation}

```
\label{eq:partial P_i(t)}{partial age_i} = \frac{\partial E[M_i(t)]}{\partial age_i} \cdot (1 + \label{eq:partial COM}(t)) \cdot (1 + \pi(t))
```

 $label{eq:110}$

\end{equation}

\begin{equation}

 $\frac{E[M_i(t)]}{\sqrt{1 + 1}}$

 $label{eq:111}$

\end{equation}

Therefore: \begin{equation}

```
\frac{P_i(t)}{\theta_i(t)}
```

 $label{eq:112}$

\end{equation}

For the second derivative, empirical data consistently show an exponential relationship between age and healthcare costs. This can be modeled by including a quadratic term for age in the expected cost function:

\begin{equation}

$$\begin{split} E[M_i(t)] &= \beta_0(t) + \beta_1(t) \cdot \ age_i + \beta_2(t) \cdot \ age_i^2 + \sum_{j=3}^{k} \\ \beta_j(t) \cdot \ X_{ij}(t) \end{split}$$

 $label{eq:113}$

\end{equation}

Where $\frac{1}{2}(t) > 0$.

Taking the second derivative:

\begin{equation}

 $label{eq:114}$

 $end{equation}$

And therefore:

\begin{equation}

 $\label{eq:partial_2_price} $$ \frac{1}{t} = \frac{1}{2} = \frac{1}{2} = \frac{1}{2} - \frac{1}$

 $label{eq:115}$

 $end{equation}$

This proves that premiums increase with age at an accelerating rate.

Implication: Commercial systems create access challenges for older individuals as populations age, with premiums becoming increasingly unaffordable for those most likely to need coverage.

8.4 Proposition 4: C&C Trust-Premium Relationship

Proposition 4: The C&C model demonstrates a unique inverse relationship between trust and required premiums while maintaining benefit levels:

\begin{equation}

 $\frac{P(t)}{TR(t)} = -\frac{B(t)}{times} (1 + \lambda (t)) \{N(t) \in TR(t)^2\} < 0$

 $label{eq:116}$

\end{equation}

Proof:

In the C&C model, premiums are determined as:

\begin{equation}

 $P(t) = \frac{B(t) \times (1 + \operatorname{lambda}(t))}{N(t) \times (R(t))}$

 $label{eq:117}$

Copyright © 2025 David M. Dror This work is licensed under the Creative Commons Attribution 4.0 International License (CC BY 4.0). To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/ \end{equation}Where:

- \$B(t)\$: Expected benefit payouts
- \$\lambda(t)\$: Loading factor
- \$N(t)\$: Number of participants
- TR(t): Trust factor affecting participation rate $(0 < TR(t) \setminus [0])$

Taking the partial derivative with respect to \$TR(t)\$:

\begin{equation}

```
\label{eq:partial P(t)}{P(t)} = \frac{TR(t)}{P(t)} = \frac{TR(t)}{B(t)} (1 + \frac{1}{N(t)})
```

 $label{eq:118}$

\end{equation}

Applying the quotient rule:

\begin{equation}

 $\times N(t) \times 1$ {(N(t) $\times TR(t)^2$ }

 $label{eq:119}$

\end{equation}

Simplifying:

\begin{equation}

 $\frac{P(t)}{\operatorname{R}(t)} = -\frac{B(t)}{\operatorname{R}(t)} = -\frac{B(t)}{\operatorname{R}(t)}$

 $label{eq:120}$

 $end{equation}$

Since B(t), $(1 + \lambda tambda(t))$, N(t), and TR(t) are all positive:

\begin{equation}

```
\frac{P(t)}{\nabla P(t)}
```

 $label{eq:121}$

\end{equation}

This proves the inverse relationship between trust and premiums.

Implication: Trust operates as a form of social capital in the C&C model that can reduce financial requirements while maintaining the same level of benefits, a property absent in other insurance models.

8.5 Proposition 5: Comparative Demographic Sustainability Thresholds

Proposition 5: Each insurance model exhibits a distinct critical threshold for demographic sustainability ($D_{crit}(t)$), ordered as follows:

\begin{equation}

 $D_{crit}^{OM}(t) > D_{crit}^{B}(t) > D_{crit}^{V}(t) > D_{crit}^{C}(t)$

 $label{eq:122}$

\end{equation}

Proof:

For each model, we define the critical demographic threshold as the dependency ratio at which the system can no longer maintain equilibrium without structural changes:

1. **Bismarckian threshold**: The point where required contribution rates exceed maximum feasible rates:

\begin{equation}

 $\label{eq:crit}^{B}(t) = \left\{ TB_B(t) + A_B(t) \right\} \\ 2 \quad (dot \ I_{average}(t) \quad (dot \ R_B(t) \ (dot \ R_B(t)$

 $label{eq:123}$

\end{equation}

Where C_{\max} is the maximum politically/economically feasible contribution rate.

 Beveridgean threshold: The point where service access falls below minimum acceptable levels:

\begin{equation}

 $D_{\operatorname{crit}}^{V}(t) = \operatorname{HC}'(t) \{v_{\min} \setminus \operatorname{cdot} (1 + \operatorname{lambda}_V(t))\} - 1$

 $label{eq:124}$

\end{equation}

Where v_{\min} is the minimum acceptable access factor.

 Commercial threshold: The point where the average premium exceeds average willingness to pay:

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\begin{equation}

 $D_{crit}^{COM}(t) = \frac{E[M_{base}(t)]}{(1 + \lambda_{ambda}(COM)(t))} (t) + \frac{1}{V(t)} WTP_{avg}(t) \ cdot \ (1 + \lambda_{amma})$

 $label{eq:125}$

\end{equation}

Where \$\gamma\$ represents the age-premium elasticity factor.

4. **C&C threshold**: The point where participation falls below minimum viable pooling or trust erodes below a critical level:

\begin{equation}

 $\label{eq:linear_line$

 $label{eq:126}$

\end{equation}

To establish the ordering, we compare system behaviors under demographic pressure:

- 1. **Commercial systems** rely on risk-based premiums that increase exponentially with age, as shown in Proposition 3. This creates affordability thresholds that are reached at relatively high dependency ratios.
- 2. **Bismarckian systems** face non-linear increases in contribution rates with demographic aging, as shown in Proposition 1, but the community rating principle creates broader risk pooling than Commercial systems.

- 3. **Beveridgean systems** adjust service access rather than premiums or contributions, as shown in Proposition 2, allowing them to maintain universal coverage at lower dependency ratios.
- C&C systems incorporate trust as a buffer mechanism against demographic pressure, as shown in Proposition 4, potentially allowing them to maintain sustainability at lower dependency ratios if trust correlates positively with age.

Empirical estimates from healthcare systems literature and demographic modeling suggest:

- Commercial systems become unstable at dependency ratios below 4:1
- Bismarckian systems can function at ratios of 3:1
- Beveridgean systems remain functional at ratios of 2.5:1
- C&C systems, due to their trust dynamics, can function at ratios of 2:1

Therefore: \begin{equation}

 $D_{crit}^{OM}(t) > D_{crit}^{B}(t) > D_{crit}^{V}(t) > D_{crit}^{C}(t)$

 $label{eq:127}$

\end{equation}

Implication: The C&C model demonstrates superior resilience to demographic pressure compared to other models, maintaining equilibrium at lower dependency ratios due to its unique trust-based sustainability mechanism.

8.6 Proposition 6: Value Proposition Expansion in the C&C Model

Proposition 6: The C&C model generates additional value components absent in conventional models:

\begin{equation}

 $V_C(t) = V_{\text{risk}}(t) + V_{\text{pref}}(t) + V_{\text{social}}(t)$

 $label{eq:128}$

 $end{equation}$

While conventional models are limited to:

\begin{equation}

 $V_{conv}(t) = V_{risk}(t)$

 $label{eq:129}$

\end{equation}

Proof:

The value of insurance to an individual can be decomposed into three components:

- Risk protection value (\$V_{risk}(t)\$): The utility gained from financial protection against uncertain health expenses.
- Preference alignment value (\$V_{pref}(t)\$): The utility gained when covered services match individual preferences.
- Social capital value (\$V_{social}(t)\$): The utility gained from community participation and governance.

In Bismarckian, Beveridgean, and Commercial models, the value function is primarily:

\begin{equation}

 $V_{conv}(t) = V_{risk}(t)$

 $\label{eq:130}$

\end{equation}

This can be mathematically represented as the expected utility difference between insured and uninsured states:

\begin{equation}

 $V_{risk}(t) = E[U(W - P_i(t) - L + B_i(t))] - E[U(W - L)]$

 $label{eq:131}$

\end{equation}

Where:

- \$W\$: Initial wealth
- \$P_i(t)\$: Premium/contribution
- \$L\$: Potential loss (healthcare costs)
- \$B_i(t)\$: Insurance benefits
- \$U\$: Utility function

In the C&C model, the community involvement in benefit design creates preference alignment value:

\begin{equation}

 $V_{pref}(t) = \sum_{s \in \mathbb{Z}} u_{i,s}(t) \quad \forall d_s(t) - \sum_{s \in \mathbb{Z}} u_{i,s}(t) \quad \forall d_s(t) - \sum_{s \in \mathbb{Z}} u_{i,s}(t) \quad \forall d_s(t) - u_{i,s}(t) \quad \forall d_s(t) \quad \forall d_s(t) - u_{i,s}(t) \quad \forall d_s(t) \quad \forall d_s(t)$

 $label{eq:132}$

\end{equation}

Where S_c is the community-determined service set and S_{reg} is a regulated standard service set.

Additionally, the governance structure creates social capital value:

\begin{equation}

 $V_{\text{social}}(t) = \det \operatorname{TR}(t) \det g_N(t)$

 $label{eq:133}$

\end{equation}

Where \pm is a social capital coefficient, TR(t) is the trust factor, and $g_N(t)$ is the participation growth rate.

Therefore, the total value in the C&C model is:

\begin{equation}

 $V_C(t) = V_{\text{risk}}(t) + V_{\text{pref}}(t) + V_{\text{social}}(t) > V_{\text{conv}}(t)$

 $\label{eq:134}$

\end{equation}

Copyright © 2025 David M. Dror This work is licensed under the Creative Commons Attribution 4.0 International License (CC BY 4.0). To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/ This expanded value function can be empirically validated through willingness-to-pay studies, which consistently show that individuals in community-based insurance schemes are willing to pay premiums that exceed actuarially fair rates, even when controlling for risk aversion (Donfouet et al., 2013; Dror et al., 2007). This "excess willingness to pay" represents the combined value of preference alignment and social capital formation.

Implication: The C&C model creates value beyond mere risk protection, offering additional utility through preference alignment and social capital formation that is absent in conventional insurance models.

9. Comparative Analysis of Mathematical Properties

9.1 Revenue Generation Mechanisms

The four models exhibit fundamentally different mathematical structures for revenue generation:

1. Bismarckian (Income-Proportional Contributions): \begin{equation}

TC_B(t) $\ \sum_{i=1}^{n} I_i(t) \ (C_e(t) + C_w(t))$

 $\label{eq:49}$

 $end{equation}$

2. Beveridgean (Tax-Based Allocation): \begin{equation}

 $TC_V(t) \ (i=1)^{n} \ (I_i(t)) \ (imes \ I_i(t) \ (alpha(t))$

 $\label{eq:50}$

 $end{equation}$

3. Commercial (Risk-Based Premiums): \begin{equation}

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 $end{equation}$

4. C&C (Trust-Based Voluntary Participation): \begin{equation}

 $TC_C(t) \setminus P(t) \setminus R(t) \setminus R(t)$

 $label{eq:52}$

 $end{equation}$

These structures reveal fundamentally different dependencies: Bismarckian systems depend critically on workforce size and income levels, Beveridgean on the broader tax base and allocation decisions, Commercial on risk assessment and market competition, and C&C on participation rates and trust levels.

Table 1: Comparative Mathematical Properties of Health Insurance Models.

Property	Bismarckian	Beveridgean	Commercial	C&C
Revenue Generation	Income-based contributions: $TC \propto \sum I_i(t) \cdot (C_e + C_w)$	Progressive taxation: $TC \propto \sum \tau(I_i(t)) \cdot I_i(t) \cdot \alpha(t)$	Risk-based premiums: TC ∝ Σ E[M_i(t)]·δ_i(t)	Trust-based community premiums: TC ∝ N(t)·P(t)·TR(t)
Equilibrium Mechanisr	n Contribution Rate Adjustment	Service Access Rationing	Risk-Based Premium Adjustment	Trust-Mediated Participation
Risk Pooling Approach	Income-Based Risk Pooling	Population-Wide Risk Pooling	Risk Segmentation by Classification	Community-Based with Trust Buffer
Demographic Vulnerabil	Non-Linear Contribution Increases	Service Access Contraction	Accelerating Premium Growth	Trust-Buffered Adjustment
ical Demographic Three	shold 3:1	2.5:1	4:1	2:1
Value Proposition	V_risk(t)	V_risk(t)	V_risk(t)	V_risk(t) + V_pref(t) + V social(t)

 Table 1: Comparative Mathematical Properties of Health Insurance Models

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Note: Mathematical expressions represent the primary functions defining each model's distinctive properties. Source: Author's formulation based on mathematical analysis.

Source: Author's formulation based on mathematical analysis.

9.2 Equilibrium Maintenance Mechanisms

Each model maintains equilibrium through different mathematical mechanisms:

1. **Bismarckian**: Contribution rates adjust to meet expenditures \begin{equation}

 $C_w(t) = \frac{TB_B(t) + A_B(t)}{2 \det n \det I_{average}(t) \det D(t)}$

 $label{eq:53}$

 $end{equation}$

2. Beveridgean: Service access adjusts to meet budget constraints \begin{equation}

 $v_s(t) = f \left(\frac{HC(t)}{D(t)}, p_s(t) \right)$

 $\label{eq:54}$

 $end{equation}$

3. **Commercial**: Premiums and risk selection adjust to maintain profitability \begin{equation}

 $P_i(t) = E[M_i(t)] \ (1 + \lambda M da_{COM}(t)) \ (1 + \mu(t))$

 $\label{eq:55}$

 $end{equation}$

4. C&C: Participation and trust dynamics adapt through community feedback \begin{equation}

 $TR(t+1) = TR(t) + \det times [CS(t) - TR(t)]$

 $label{eq:56}$

\end{equation}

These different equilibrium mechanisms create distinct responses to demographic and financial pressures.

9.3 Demographic Sensitivity Comparison

The mathematical sensitivity to demographic changes reveals distinct vulnerability patterns:

1. **Bismarckian**: \begin{equation}

 $\label{eq:constraint} $$ \int dC_w(t) dD(t) = -\int a(A_B(t)) dD(t) dD(t) = -\int a(A_B(t)) dD(t) dD(t)$

 $\label{eq:57}$

 $end{equation}$

Non-linear increase in contribution rates as the dependency ratio decreases.

2. **Beveridgean**: \begin{equation}

 $\frac{D(t)}{\int C(t)} = \frac{D(t)}{\int C(t)}$

HC(t) { $D(t)^{2}$ } > 0

 $label{eq:58}$

 $end{equation}$

Service access contracts as the population ages.

3. Commercial: \begin{equation}

 $label{eq:59}$

```
end{equation}
```

Premiums increase at an accelerating rate with age, potentially leading to coverage gaps.

4. C&C: \begin{equation}

 $\frac{P(t)}{\operatorname{R}(t)} = -\frac{B(t)}{\operatorname{R}(t)} = -\frac{B(t)}{\operatorname{R}(t)}$

< 0

```
label{eq:60}
```

```
end{equation}
```

Trust dynamics can potentially buffer demographic pressures if social capital increases with age in communities.

As established in Proposition 3, these differences create a clear ordering of critical demographic thresholds: $D_{crit}^{OM}(t) > D_{crit}^{B}(t) > D_{crit}^{V}(t) > D_{crit}^{C&C}(t)$



Figure 1: System Response to Declining Dependency Ratios

Note: Higher curves indicate greater system stress response to demographic changes.

Figure 1: System Response to Declining Dependency Ratios.

The figure shows how each system's key variables adjust as dependency ratios decline from 4:1 to

2:1, with higher curves indicating greater system stress.

Source: Author's derivation based on equations (57)-(60).

9.4 Risk Pooling Approaches

The four models implement mathematically distinct risk pooling approaches:

 Bismarckian: Risk is pooled across income levels, with higher incomes subsidizing lower incomes. \begin{equation}

 $P_i(t) = [C_e(t) + C_w(t)] \text{ times } I_i(t)$

 $\label{eq:61}$

 $end{equation}$

 Beveridgean: Risk is pooled across the entire population through general taxation. \begin{equation}

\tau(I_i(t)) \propto \text{Progressive function of income}

 $label{eq:62}$

 $end{equation}$

 Commercial: Risk is segmented through classification, creating separate risk pools. \begin{equation}

 $\frac{1}{r_1, r_2, \ldots, r_m}$

 $\label{eq:63}$

 $end{equation}$

4. C&C: Risk is pooled within communities with trust as a binding mechanism. \begin{equation}

 $P(t) = \frac{B(t) \times (1 + \operatorname{lambda}(t))}{N(t) \times (TR(t))}$

 $label{eq:64}$

 $end{equation}$

These differences in risk pooling create fundamentally different system behaviors and vulnerabilities.

9.5 Administrative Cost Structures

Administrative costs follow different mathematical patterns across models:

1. **Bismarckian**: \begin{equation}

 $A_B(t) = beta_B \times TC_B(t) + amma_B \times N(t)$

 $\label{eq:65}$

 $end{equation}$

2. Beveridgean: \begin{equation}

 $A_V(t) = beta_V \in HC(t)$

 $label{eq:66}$

 $end{equation}$

3. Commercial: \begin{equation}

 $\label{eq:a_com} A_{COM}(t) = \beta_{COM} \times TC_{COM}(t) + \gamma_{COM} \times n + \times m$

 $label{eq:67}$

 $end{equation}$

Where \$n\$ is the number of insurees and \$m\$ is the number of risk classes.

4. C&C: \begin{equation}

 $A_C(t) = \beta C \otimes TC_C(t) + \beta M(t) \otimes N(t)$

 $\label{eq:68}$

\end{equation}

The C&C model uniquely incorporates trust as a factor in administrative efficiency, creating potential for lower administrative costs as trust increases.

10. Model Resilience to System Stressors

To further examine the distinctive properties of the four models, we analyze their mathematical resilience to three critical system stressors: demographic aging, economic downturns, and information asymmetry.



Note: Higher values (scale 1-5) indicate greater resilience to the corresponding stressor.

Figure 2: Comparative Resilience Profiles.

The radar chart compares each model's resilience to demographic aging, economic downturns, and information asymmetry on a scale from 1 (low) to 5 (high).

Source: Author's quantification based on elasticity measures in equations (69)-(84).

10.1 Resilience to Demographic Aging

Demographic aging affects all health insurance systems through decreasing dependency ratios. The mathematical resilience can be assessed through elasticity measures.

Definition 1: The demographic elasticity of system sustainability (\$E_D\$) is defined as:

\begin{equation}

 $E_D(t) = \frac{S(t)}{S(t)}$

 $\label{eq:69}$

\end{equation}

This measures the percentage change in sustainability function in response to percentage changes in the dependency ratio.

For Bismarckian systems: \begin{equation}

 $E_D^B(t) = \frac{C}{C} \left\{ K \right\} = \frac{K}{S_B(t)} = \frac{K}{S_B(t)}$

 $label{eq:70}$

 $end{equation}$

For Beveridgean systems: \begin{equation}

 $E_D^V(t) = \frac{-HC(t)}{\cot D(t)^{-2}} \det D(t) \{S_V(t)\} = \frac{-HC(t)}{S_V(t)} = \frac{-HC(t)}{S_V(t)}$

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57

 $label{eq:71}$

 $end{equation}$

For Commercial systems: \begin{equation}

 $E_D^{COM}(t) = \frac{\sum_{i=1}^n \frac{P_i(t)}{\beta \alpha \alpha \beta \alpha}}$ age_i}{\partial D(t)} \cdot \delta_i(t)}{S_{COM}(t)} \cdot D(t)

 $label{eq:72}$

 $end{equation}$

For C&C systems: \begin{equation}

$$\begin{split} E_D^C(t) &= \frac{N(t) \quad P(t) \quad TR(t)}{\rho_t \quad D(t)} + N(t) \quad D(t) \\ \frac{D(t)}{\int D(t)} \quad D(t) \quad Cdot \quad TR(t) + \frac{D(t)}{\int D(t)} \quad Cdot \quad P(t) \quad Cdot \quad TR(t)}{S_C(t)} \\ \end{split}$$

 $label{eq:73}$

\end{equation}

Under reasonable parameterizations and positive trust correlation with age: \begin{equation}

 $|E_D^{A}C(t)| < |E_D^{A}B(t)| \mid text\{ and \} |E_D^{A}C(t)| < |E_D^{A}\{COM\}(t)|$

 $label{eq:74}$

 $end{equation}$

This implies that the C&C model demonstrates greater mathematical resilience to demographic aging than either Bismarckian or Commercial systems.

10.2 Resilience to Economic Downturns

Economic downturns stress health insurance systems through reduced revenues and increased demand for services. The mathematical resilience can be assessed through income elasticity measures.

Definition 2: The income elasticity of system sustainability (\$E_I\$) is defined as:

\begin{equation}

 $E_I(t) = \frac{S(t)}{\nabla I(t)} \\ S(t) \\ S$

 $\label{eq:75}$

 $end{equation}$

Where $\operatorname{Verline}\{I\}(t)\$ represents average income.

For Bismarckian systems: \begin{equation}

 $E_I^B(t) = \frac{TC_B(t)}{\operatorname{TC}B(t)} = \frac{I}(t) + \frac{I}(t) +$

 $label{eq:76}$

 $end{equation}$

For Beveridgean systems: \begin{equation}

$$\label{eq:label} \begin{split} E_I^V(t) &= \frac{\hat{I}(t)}{S_V(t)} \\ \cdot \sum_{i=1}^n \frac{I_i(t)}{cdot I_i(t)} \end{split}$$

 $label{eq:77}$

 $end{equation}$

For Commercial systems: \begin{equation}

$$\begin{split} E_I^{COM}(t) &= \frac{\sum_{i=1}^n \det_i(t) \cdot \det_I(t)}{\left(\sum_{i=1}^n \det_i(t) \cdot \det_I(t)\right)} \\ & \det_I(t) \in I_{t}(t) \in I_{t}(t) \\ & \det_I(t) \in I_{t}(t) \in I_{t}(t) \\ & \det_I(t) \\ & \det_I(t) \in I_{t}(t) \\ & \det_I(t) \in I_{t}(t) \\ & \det_I(t) \\ & \det_I$$

 $label{eq:78}$

 $end{equation}$

For C&C systems: \begin{equation}

$$\begin{split} E_I^C(t) &= \frac{\left[N(t) \ Cdot \ P(t) \ TR(t)\right]}{\left[\operatorname{Verline}\{I\}(t)\}} \right] \\ & \int_{\mathbb{T}^2} \left[S_C(t) \right] \\ \end{split}$$

 $label{eq:79}$

\end{equation}

Under conditions where trust is less volatile than income: \begin{equation}

 $|E_I^C(t)| < |E_I^B(t)| \text{ text} \{ \text{ and } \} |E_I^C(t)| < |E_I^V(t)|$

 $label{eq:80}$

\end{equation}

This suggests that the C&C model potentially offers greater mathematical resilience to economic downturns than either Bismarckian or Beveridgean systems.

10.3 Resilience to Information Asymmetry

Information asymmetry creates adverse selection pressures in health insurance systems. The mathematical resilience can be assessed through information elasticity measures.

Definition 3: The information elasticity of system sustainability (\$E_{IA}\$) is defined as:

\begin{equation}

 $E_{IA}(t) = \frac{S(t)}{S(t)}$

 $label{eq:81}$

 $end{equation}$

Where \$IA(t)\$ represents an index of information asymmetry.

For Commercial systems: \begin{equation}

 $E_{IA}^{COM}(t) = \frac{Pi(t)}{Pi(t)} + Cot \frac{IA(t)}{S_{COM}(t)} < 0$

 $\label{eq:82}$

\end{equation}

For C&C systems: \begin{equation}

$$\begin{split} E_{IA}^C(t) &= \frac{\left[N(t) \ Cdot \ P(t) \ TR(t)\right]}{\left[P(t) \ IA(t)\right]} \\ & \int Fac_{IA}(t) \\ & \int Fac_{I$$

 $label{eq:83}$

\end{equation}

When trust mechanisms effectively counteract information asymmetry: \begin{equation}

 $|E_{IA}^C(t)| < |E_{IA}^{(COM)}(t)|$

Copyright © 2025 David M. Dror This work is licensed under the Creative Commons Attribution 4.0 International License (CC BY 4.0). To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/ $\label{eq:84}$

\end{equation}

This indicates that the C&C model may demonstrate greater mathematical resilience to information asymmetry than Commercial systems.

11. Theoretical Implications and Conclusions

11.1 Key Theoretical Findings

Our mathematical taxonomy of health insurance models reveals fundamental structural differences that extend beyond policy descriptions. Each model incorporates distinct mathematical mechanisms for generating revenue, pooling risk, determining benefits, and maintaining equilibrium.

- 1. **Structural Uniqueness**: Each model possesses mathematically distinctive structures that create different incentives, vulnerabilities, and adaptation mechanisms.
- 2. **Demographic Sensitivity**: All four models exhibit sensitivity to demographic change, but through different mathematical pathways and with different non-linear properties.
- Equilibrium Mechanisms: The models maintain financial equilibrium through fundamentally different mathematical adjustment processes—contribution rates (Bismarckian), service access (Beveridgean), risk-based premiums (Commercial), and trust-mediated participation (C&C).
- 4. **Trust as a Mathematical Variable**: The C&C model uniquely incorporates trust as an explicit mathematical variable in its core equations, creating distinctive properties not present in conventional models.

5. Value Function Expansion: The C&C model mathematically expands the value proposition beyond risk protection to include preference alignment and social capital formation.

11.2 Implications for Health System Design

The mathematical taxonomy developed in this paper has several implications for health system design:

- 1. **Model Selection**: The choice between models should consider their mathematical properties and alignment with policy objectives, not just descriptive features.
- 2. **Hybrid Systems**: Many real-world systems incorporate elements of multiple models, suggesting the need for mathematical frameworks that can analyze hybrid structures.
- 3. **Vulnerability Assessment**: The mathematical vulnerability of different models to demographic, economic, and social pressures can be quantitatively assessed using the framework developed.
- Innovation Pathways: The distinctive mathematical properties of the C&C model suggest innovation pathways for conventional systems seeking resilience in challenging environments.



Figure 3: Potential System Hybridization Pathways

Figure 3: Potential System Hybridization Pathways.

The diagram illustrates how mathematical elements from different models could be combined to create enhanced systems with improved resilience properties.

Source: Author's conceptualization based on comparative mathematical analysis.

11.3 Policy Implications

The mathematical analysis leads to several policy implications. First, systems facing rapid demographic aging should consider mathematical structures that moderate sensitivity to dependency ratio changes, potentially incorporating elements of the C&C model. Fan et al. (2021) show that strategic investment in appropriate health system structures can yield substantial

returns for economic growth and population health, underscoring the importance of selecting mathematically resilient insurance models.

- 1. **Demographic Resilience**: Systems facing rapid demographic aging should consider mathematical structures that moderate sensitivity to dependency ratio changes, potentially incorporating elements of the C&C model.
- 2. Economic Stability: During economic downturns, systems' adjustment mechanisms operate differently, with Beveridgean systems likely to restrict access while Commercial systems may intensify risk selection. Policy measures should anticipate these mathematical responses.
- 3. **Trust Development**: The mathematical role of trust in the C&C model suggests that policies promoting transparency, community engagement, and social capital formation may enhance health system sustainability.
- 4. **Information Asymmetry Management**: Commercial systems require regulatory frameworks to constrain adverse selection dynamics, while C&C systems may leverage trust mechanisms to partially counteract information asymmetry effects.

11.4 Research Directions

This work points to several promising research directions:

- 1. **Empirical Parameterization**: Estimating model parameters using real-world data from different health systems.
- Simulation Modeling: Developing dynamic simulation models to test the behavior of different systems under stress conditions.

- 3. **Hybrid Model Analysis**: Creating mathematical frameworks for analyzing systems that incorporate elements of multiple models.
- 4. **Trust Dynamics**: Further exploration of the mathematical properties of trust in health insurance contexts.
- 5. Formalization of Governance Effects: Extending the mathematical framework to incorporate governance structures and their effects on system behavior.

11.5 Conclusion

The mathematical taxonomy developed in this paper provides a rigorous foundation for comparative analysis of health insurance models. By formalizing the core structures and dynamics of four principal models, it enables precise identification of their distinctive properties, vulnerabilities, and potential for adaptation. This approach moves beyond descriptive comparisons to reveal fundamental mathematical differences that shape system behavior under various conditions.

The emergence of the C&C model, with its distinctive trust-based mathematical structure, suggests new possibilities for health insurance design that may offer resilience in contexts where conventional models face challenges. Further development of this mathematical framework will support both theoretical advances in health system analysis and practical innovations in health insurance design.

While no single model emerges as universally superior across all dimensions, the mathematical taxonomy enables more precise matching of model characteristics to specific contextual requirements. In particular, the C&C model's unique incorporation of trust as a mathematical variable offers a potential pathway for addressing sustainability challenges in environments where demographic, economic, and information asymmetry pressures are significant.

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