System Dynamics Modeling: Overview & Causal Loop Diagrams

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What is System Dynamics?

- A feedback-oriented perspective

- A broad, evolving methodology to help
  Conceptualize
  Describe
  Analyze
  Manage
  feedback systems
System Dynamics offers…

• Qualitative & quantitative components
• A defined, incremental and iterative modeling process that delivers value throughout
• Time-honed techniques for working with diverse interdisciplinary stakeholders
• Evolved software permitting focus on the “what” is being described – not how it is run
• A rigorous mathematical foundation
• A rich set of analysis tools
• Techniques for interfacing closely with cognate areas (e.g. statistics, decision sciences, evidence-based practices, applied mathematics, other modeling approaches, etc.)
Differences in Framing the Issues

• Modeling methodologies are often distinguished more fundamentally by the questions being asked than by the answers being given.
• Such methodologies will often be most distinguished by the way in which they frame problems.
• In comparing, we must be conscious of these differences.
Engagement in the Human Theatre
Uses of SD Models [Hovmand]

Radical Change Views of Society

| Learning problems: Models that facilitate learning how to prevent or manage disease |
| Restructuring problems: Models that transform the way a group is seeing disease |

Objective Views of Social Science

| Coordination problems: Models that develop a shared view of disease and help coordinate action |
| Analysis problems: Models that lead to better estimates of the risks and identify leverage points |

Subjective Views of Social Science

Power to the People: Fostering Participatory Discourse

- To empower participatory modeling, System Dynamics tends towards simpler formalisms
  - Capturing qualitative understanding
  - Easy understanding by stakeholders: Simulation model
    - Inspection
    - Dialogue
    - Manipulation
  - Declarative (“programming free”) specification
  - Intuitive graphical representation

Features support high stakeholder involvement in model conceptualization, formulation & analysis
Stages of the System Dynamics Modeling Process

A Key Deliverable!

Model scope/boundary selection.
Model time horizon identification of key variables
Reference modes for explanation

Causal loop diagrams
Stock & flow diagrams
Policy structure diagrams
Group model building

Specification of
• Parameters
• Quantitative causal relations
• Decision rules
Initial conditions
Constrain to sensible bounds
Structural sensitivity analysis

Reference mode reproduction
Matching of intermediate time series
Matching of observed data points

Parameter sensitivity analysis
Cross-validation
Robustness & extreme case tests
Unit checking
Problem domain tests
Formal analysis

Specification & investigation of intervention scenarios
Investigation of hypothetical external conditions
Cross-scenario comparisons (e.g., CEA)

Learning environments/Microworlds/flight simulators

Qualitative & Semi-quantitative insights

Quantitative insights
Value of the Modeling Process

- Often the *modeling process* itself – rather than the models created – offers the greatest value
- Modeling as theory building: Refinement of mental models
- Reflecting on
  - Mental models
  - What is & is not known / data
  - Different perspectives
Benefits of Rich Stakeholder Participation

- Developing rich, grounded understanding
- Building community capacity
- Critiquing model behavior
- Fostering stakeholder cooperation
- Implementing policy recommendations
- Facilitating data collection design
- Aiding in replanning
- Keeping model updated
- Empowering community self-guidance
- “Dignity of Risk” [Hovmand]
Group Model Building [Hovmand]
Group Model Building [Hovmand]
Model Conceptualization: Feedback Loops

- Loops in a causal loop diagram indicate feedback in the system being represented.
  - Qualitatively speaking, this indicates that a given change kicks off a set of changes that cascade through other factors so as to either amplify ("reinforce") or push back against ("damp", "balance") the original change.

- Loop classification: product of signs in loop (best to trace through conceptually)
  - Balancing loop: Product of signs negative
  - Reinforcing loop: Product of signs positive
Example: Physical Systems With & Without Feedbacks

• Balancing
• Driving / flying
• Thermic regulation: “Hot blooded” (homeothermy) vs. “cold blooded” (ecoothermic) animals

Introducing a feedback can fundamentally alter a system’s behaviour
Recall: A Common Problem: Overly Narrow Mental Models

- Most decisions are based on mental models
- Frequently the failure to anticipate & account for policy resistance is due to narrow mental models
  - Deleterious effects are blamed on “side effects” of anticipated process
  - Failure to consider interactions between diverse pieces of system (each of which may be well understood)
- System dynamics seeks a broader understanding of the underlying system
Examples of Deleterious Feedbacks

• Cutting cigarette tar levels reduces cessation
• Cutting cigarette nicotine levels leads to compensatory smoking
• Targeted anti-tobacco interventions lead to equally targeted coupon programs by tobacco industry
• Charging for supplies for diabetics leads to higher overall costs by increases costs due to reduced self-management, faster disease progression
• ARVs prolong lives of HIV carriers, but lead to resurgent HIV epidemic due to lower risk perception
• “Saving money” by understaffing STI clinics, leads to long treatment wait, greater risk of transmission by infectives & bigger epideims
• Antibiotic overuse worsens pathogen resistance
• Antilock breaks lead to more risky driving
• Natural feedback: Intergenerational “Vicious Cycles”
Causal Loop Diagram

- Focuses on capturing causality – and especially feedback effects
- Indicates sign of causal impact (+ vs. –)

- \( x \rightarrow^+ y \) indicates \( \frac{\partial y}{\partial x} > 0 \)
- \( x \rightarrow^- y \) indicates \( \frac{\partial y}{\partial x} < 0 \)
Causal Loop Diagram

– An arrow with a positive sign (+): “all else remaining equal, an increase (decrease) in the first variable increases (decreases) the second variable above (below) what it would otherwise have been.”

– An arrow with a negative sign (-): “all else remaining equal, an increase (decrease) in the first variable decreases (increases) the second variable below (above) what it otherwise would have been.”
Reasoning about Link Polarity

• Easy to get confused regarding link polarity in the context of a causal chain

• Tips for reasoning about link polarity for X→Y

  • Reason about this link in isolation
    • Do not be concerned about links preceding X or following Y
  
  • Ask “if X were to INCREASE, would Y increase or decrease”?  
    • Increase in Y implies “+”, decrease in Y implies “-”
    • If answer is not clear or depends on value of X, need to think about representing several paths between X and Y
Tips

• Variables should be noun phrases
• Variables should be at least ordinal
• Links should have unambiguous polarity
• Remember factors involving people
• Avoid mega-diagrams
• Label loops
• Distinguish perceived and actual situation
• Incorporate targets of balancing loops
Ambiguous Link

- Ambiguous Link: Sometimes +, sometimes -
  
  Replace this by disaggregating causal pathways by showing multiple links.

Overtime → Work Accomplished per Day

Overtime

Fatigue

Efficiency

Greater Incorporation of Outside Tasks at Work

More Time Working

Work Accomplished per Day
Feedback Loops

• Loops in a causal loop diagram indicate *feedback* in the system being represented

  • Qualitatively speaking, this indicates that a given change kicks off a set of changes that cascade through other factors so as to either amplify (“reinforce”) or damp (“balance”) original change

• Loop classification: product of signs in loop (best to trace through conceptually)
  
  Balancing loop: Product of signs negative

  Reinforcing loop: Product of signs positive
Dysphoria & Stress
Substance Abuse
Costs
Employability
Stigmatization
+
-
Nutrition
Risk of Injury & Accidents
+
+
Health
Poverty
-
+
+
+
-
+
Capacity for Productive Work
Impulse towards Self-Medication

Reinforcing (positive) feedback

Balancing (negative) feedback
## Advantages of Recognizing Feedback

<table>
<thead>
<tr>
<th>Desirable</th>
<th>Balancing Feedback (Stability)</th>
<th>Reinforcing feedback (Instability)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Securing resiliency</strong></td>
<td>Individual self-regulation</td>
<td><strong>Enabling rapid intervention success</strong></td>
</tr>
<tr>
<td><strong>Structure interventions (and system) to achieve this</strong></td>
<td></td>
<td><strong>Viral approaches, peer messaging, rapid social change</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Undesirable</th>
<th>Preventing policy resistance &amp; adverse “lock in” effects</th>
<th>Heading off rapidly growing vicious cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>...and prevent this</strong></td>
<td>Low tar &amp; nicotine cigarettes Risk perception for Infectious diseases</td>
<td>Addictions, “cycle of poverty”, SAVA</td>
</tr>
</tbody>
</table>
Gates’ Comments

“The biggest advantage we have is that good developers like to work with good developers”
• [Cusumano&Selby, ’95]

“Most people don’t get millions of people giving them feedback about their products...We have this whole group of [2000] people in the US alone that takes phone calls about our products and logs everything that’s done. So we have a better feedback loop, including the market”
• [Cusumano&Selby, ’95]

“As [NT] got more applications, NT servers got more popular. As it’s gotten more popular, we’ve got more applications.”
• Computer Reseller News, 9-23-1996

“[T] he more users [the internet] gets, the more content it gets, the more users it gets.”
• Red Herring, 10-1995

“It’s all about scale economies and market share. When you’re shipping a million units of Windows software a month, you can afford to spend $300 million a year improving it and still sell at a low price.”
[Fortune, 6-14-1993]
Examples: Vicious/Virtuous Cycles

- Positive (reinforcing) feedback can lead to extremely rapid changes in situation

1. Existing Users
   - Likelihood of Cross Listing and Listing on Search Engines
   - New Users Discovering Site
2. Number of Connections to Music Download Server
   - Length of Time Per Download
3. Likelihood of User Starting Multiple Simultaneous Downloads
4. Confusing Code
   - Ease of Understanding where to Make a Change
5. Word of Mouth Sales
   - Customers
6. Confusing Additions
Simple Causal Loops

- Change Requests → Remaining Work
- Project Duration
- Overbearing PM Management Style
- PM Suspicion
- Willingness of Project Participants to share info with PM

- Changes to Schedule
- Aggregate Productivity
- Job Rhythm

- Estimated Design Costs beyond Target Budget
- Design Scope
- Target Budget
- Coordinated Work Required
- Amount of Work to Be Done
- Number of New People
- Training Load on Old Workers
- Productive Work Finished
- Relative Progress

- +
- -
- +
- -
- +
- -
Example “Balancing Loops”

• Balancing loops tend to be self-regulating

Aggregate Computer Responsiveness

Programs Run Simultaneously

Virtual Memory Swapping

Mistakes

Learning from Mistakes
Risk Management

Unmanaged Risks

Schedule Disruptions

+ Time taken for Risk Assessment and Management

-
Longer Term Cost of Pressure: Cutting Corners
Vicious Cycles
Turnover Vicious Cycle

- Developer Fatigue
- Morale
- Resignations
+ Backlog of Work
- Team Productivity
+ Extra Hiring
+ Related Work
+ Work per Team Member
- Team Productivity
Reinforcing Loop Dynamics: Exponential Growth

- **Example**
  - Word of Mouth Sales
  - Customers

- **Dynamic implications**
  - Site Popularity
  - Likelihood of Cross Listing and Listing on Search Engines

Graph for Stock

- Stock: Current
Causal Loop Dynamics: Goal Seeking (Balancing Loop)

• Example:

• Dynamic behavior
Causal Loop Dynamics: Oscillation (Balancing Loop with Delay)

- Causal Structure

- Dynamic Behavior:
Growth and Plateau

- **Loop structure:**
  - Reinforcing Loop
  - Balancing Loop

- **Dynamic Behavior:**

  From Tsai
Regulatory Mechanisms

- Overload
- Fatigue (reducing activities)
- Depression
- Morale building activities
- Low productivity
Perverse Incentives Under Stress

Diagram:

- Overload
- Fatigue
- Fatigue reducing activities
- Low productivity
- Depression
- Morale building activities

Weinberg, Quality Software management
Elaborating Causal Loops

Work Remaining

Work Pressure

Productivity

Fatigue

Work Remaining

Productivity

Fatigue
Elaborating Causal Loops 2

Project Performance
Managerial Desire to Blame
Information Availability
Quality of Management Decision Making
Managerial Trust of Developers
Developer's Trust of Manager
Information Availability
Quality of Management Decision Making
Exercise 1: Link & Loop Polarity

- Label the polarity of each link in this diagram

- What factor is missing?

- Is the feedback positive or negative?
Exercise 2: Unanticipated Side Effects

• Seeking modest investment in Blackberries for productivity enhancement

• Muddied by unanticipated side effects
Exercise 3: Link & Loop Polarity

• Create one or more causal loops relating
  • Project Morale
  • Project Turnover
  • Workload
  • Project delay

• Are these loops positive or negative?
• Do these loops all have the same time to ‘kick in’ (time constants)?
One Set of Loops

- Developer Fatigue
- Morale
- Resignations

- Backlog of Work
- Team Productivity

+ Extra Hiring
+ Related Work

+ Work per Team Member
Recall: Dealing with Symptoms vs. Causes

- Our focus is often on undesirable symptoms (high cost, schedule delay, poor quality) rather than on underlying causes
  - Often a project is in severe trouble by the time these obvious (and easily quantifiable) symptoms appear
  - Often choices of interventions fail to consider broader (and perhaps less quantifiable) effects of actions
A Consulting Case
Managerial Pressure

- Narrow mental model aims for this goal

- Unanticipated side effects “push back” vs. time savings & cause quality problems
Path Dependence/Network Effects & Lock-In

- In the presence of positive feedback, one can get “lock in” effects
- Similar early conditions result in divergent outcomes (instability)
  - Example: Product largely in balance vs. continuously in turmoil
Unstable, Critical, and Subject to Lock-in

- Software Quality
- Trust
- Respect
- Morale
Elaborating Causal Loop Diagrams: Most Basic Feedbacks
With Recovery (& Waning Immunity)
With Risk Perception-Driven Behavioral Change
...and Vaccination As Well
Blowback: Perverse Evolutionary & Behavioural Feedbacks
Incorporating Some Determinants of Health
Structure as Shaping Behaviour

- System structure is defined by
  - Stocks
  - Flows
  - Connections between them (yielding feedbacks)
- Nonlinearity: The behaviour of the whole is more than the sum of the behaviour of the parts
  - “Emergent” behaviour would not be anticipated from simple behaviour of each piece in turn
- Stock and flow structure (including feedbacks) of a system determines the qualitative behaviour modes that the system can take on (parameters determine particulars)
- Changes to the feedback structure can change behaviour in fundamental ways
Causal Loop Structure: Dynamic Implications

- Each loop in a causal loop diagram is associated with qualitative dynamic behavior

- Most Common Single-Loop Modes of Dynamic Behavior
  - Exponential growth
  - Goal Seeking Adjustment
  - Oscillation

- When composed, get novel behaviors due to shifting loop dominance
  - Behaviour of system more than sum of parts
  - e.g. Growth & Plateau, “Boom & Bust”, Lock-in
Causal Loop Dynamics: Exponential Growth (First Order Reinforcing Loop)

Examples

Dynamic implications
Causal Loop Dynamics: Goal Seeking (Balancing Loop)

- **Example:**

- **Dynamic behavior**
Causal Loop Dynamics: Oscillation (Balancing Loop with \textit{Delay})

- **Causal Structure**

- **Dynamic Behavior:**

\[
\begin{align*}
\text{Level of Risk} & \rightarrow \text{Perceived Level of Risk} \\
\text{Measures to Lessen Risk (Hygiene, Care in Mixing, etc.)} & \rightarrow \text{Perception of Dialysis Clinic Crowding Judged Appropriate, Taking into Account Perceived Benefits and Costs of Extra Capacity} \\
\text{Level of Dialysis Clinic Crowding} & \rightarrow \text{Demand for Dialysis Clinics} \\
\text{Measures Undertaken to Expand Dialysis Clinic Capacity} & \rightarrow \text{Perception of Excess in Dialysis Clinic Crowding} \\
\end{align*}
\]
Growth and Plateau

- Loop structure:
  - Reinforcing Loop
  - Balancing Loop

- Dynamic Behavior:

  From Tsai
State of the System: Stocks
(“Levels”, “State Variables”, “Compartments”)

- Stocks (Levels) represent accumulations
  - These capture the “state of the system”
- These can be measured at one instant in time
- Stocks start with some initial value & are thereafter changed only by flows into & out of them
  - There are no inputs that immediately change stocks
- Stocks are the source of delay in a system
- In a stock & flow diagram, shown as rectangles
Example Model: Stocks

- Mean Contacts Per Susceptible per Year
- Mean Infectious Contacts Per Susceptible per Year
- Total Population
- Force of Infection (Likelihood Density of Infection per Susceptible)
- Prevalence of Infection
- Recovery Delay
- Probability of Transmission between Infective and Susceptible
- Initial Population
- New Infections
- New Recovery
- Loss of Immunity Delay
- Newly Susceptible
- New Illnesses
- Cumulative Illnesses
The Critical Role of Stocks in Dynamics

- Stocks determine current state of system
  - Stocks often provide the basis for making choices
- Stocks central to most disequilibria phenomena (buildup, decay)
- Lead to inertia
- Give rise to delays
State Changes: Flows ("Fluxes", "Rates", "Derivatives")

• All changes to stocks occur via flows

• Always expressed per some unit time: If these flow into/out of a stock that keeps track of things of type $X$ (e.g. persons), the rates are measured in $X/(\text{Time Unit})$ (e.g. persons/year, $$/\text{month}, \text{gallons/second})$

• Typically measure over certain period of time (by considering accumulated quantity over a period of time)
  • e.g. Incidence Rates is calculated by accumulating people over a year, revenue is $$/\text{Time}, \text{water flow is litres/minute}$
  • Can be estimated for any point in time
Example Model: Flows

- Mean Contacts Per Susceptible per Year
- Mean Infectious Contacts Per Susceptible per Year
- Total Population
- Force of Infection (Likelihood Density of Infection per Susceptible)
- Prevalence of Infection
- Recovery Delay
- New Infections
- New Recovery
- Loss of Immunity Delay
- Newly Susceptible
- Cumulative Illnesses
- Initial Population
- New Illnesses
- Temporarily Immune
Key Component: Stock & Flow

Stocks Determine Flows

Flows Dictate Change in Stocks
Auxiliary Variables

- Auxiliary variables are convenience names we give to concepts that can be defined in terms of expressions involving stocks/flows at current time
  - Adding or eliminating an auxiliary variable does not change the mathematical structure of the system
- Critical for model transparency
  - Can be reused at many places
  - References to auxiliary variables prevents need for modeler to think about all of details of definition
- Enhanced modifiability: Single place to define
- Convenient for reporting (graphing, tables) & analyzing model dynamics
Example Model: Auxiliary Variables

- Mean Contacts Per Susceptible per Year
- Mean Infectious Contacts Per Susceptible per Year
- Total Population
- Force of Infection (Likelihood Density of Infection per Susceptible)
- Prevalence of Infection
- Probability of Transmission between Infective and Susceptible
- Recovery Delay
- Initial Population
- New Infections
- Infectious
- New Recovery
- Temporarily Immune
- Loss of Immunity Delay
- Newly Susceptible
- New Illnesses
- Cumulative Illnesses
For similar reasons to auxiliary variables, we give names to

- Model constants
- Time series
Example Model: Parameters

- Mean Contacts Per Susceptible per Year
- Mean Infectious Contacts Per Susceptible per Year
- Total Population
- Force of Infection (Likelihood Density of Infection per Susceptible)
- Prevalence of Infection
- Recovery Delay
- Loss of Immunity Delay
- Initial Population
- Temporarily Immune
- New Infections
- New Recovery
- Newly Susceptible
- Cumulative Illnesses
- New Illnesses
Example System Structure, Illustrating Feedbacks

- **Susceptibles**
  - Contacts between susceptibles & infectives per month
  - Infections

- **Infectives**
  - People being sought for or awaiting treatment/diagnosis
  - Time Until Treatment
  - Time Until Recovery

- **Recovereds**
  - Recoveries

- **Waning of Immunity**
  - Duration of Immunity
Handling Heterogeneity

Step 1: Test (via scenarios) if heterogeneity is likely to have substantive impact on results

Step 2: Where necessary, disaggregate model according to heterogeneity
- Small model: Duplicate stocks
- Larger model: Subscripting

Step 3: Express inter-group contact patterns via mixing & preference matrices
A Subscripted Model

Mixing Matrix

Totalss

Male Population

Cumulative Counts

Female Population

Stratified by:
- 17 age categories
- 2 cervical screen. groups
- 3 sexual activity groups
- 2 smoking statuses
- 2 sexes

Each visual stock represents 408 distinct underlying stocks
Example Mixing Preferences

Preferential Mixing by Age Difference
Registered Indians & Metis Cases with Contacts of Any Ethnicity

Relative Degree of Preference Cases for Mixing with Contacts in Different Age Groups

Number of (generally 5-year) Age Categories between case and contacts
Sources for Parameter Estimates

- Surveillance data
- Controlled trials
- Outbreak data
- Clinical reports data
- Intervention outcomes studies
- Calibration to historic data
- Expert judgement
- Systematic reviews

<table>
<thead>
<tr>
<th>Parameter*</th>
<th>Description</th>
<th>Baseline value (units)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$</td>
<td>Entry/exit of sexual activity</td>
<td>0.0056 (years$^{-1}$)</td>
<td>Garnett and Bowden, 2000</td>
</tr>
<tr>
<td>$c$</td>
<td>Partner change rate per Susceptible</td>
<td>16.08 (years$^{-1}$)</td>
<td>Approximated from Garnett and Bowden, 2000</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Probability of infection per sexual contact</td>
<td>0.70</td>
<td>Garnett and Bowden, 2000</td>
</tr>
<tr>
<td>$\varphi$</td>
<td>Fraction of Infectives who are symptomatic</td>
<td>0.20</td>
<td>Garnett and Bowden, 2000</td>
</tr>
<tr>
<td>$1/\gamma$</td>
<td>Latent period</td>
<td>0.038 (years)</td>
<td>Brunham et. al., 2005</td>
</tr>
<tr>
<td>$1/\sigma$</td>
<td>Duration of infection</td>
<td>0.25 (years)</td>
<td>Brunham et. al., 2005</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Asymptomatic recovery coefficient</td>
<td>1.5</td>
<td>Garnett and Bowden, 2000</td>
</tr>
<tr>
<td>$1/\pi$</td>
<td>Duration of naturally-acquired immunity</td>
<td>1 (year)</td>
<td>Approximated from Brunham et. al., 2005</td>
</tr>
</tbody>
</table>
Introduction of Parameter Estimates

Frequently System Dynamics models will provide much more detail on networks of factors shaping these rates, but ultimately there will be constants requiring specification.
Scenarios for Understanding How Does X affect System
Single Model Matches Many Data Sources

- T2DM Prevalence
- T2DM Incidence
- Total Population
- ESRD Prevalence
- ESRD Incidence
- ESRD Death
- T2DM Deaths

Graphs showing trends over time for various health indicators in diabetes and kidney disease.
Example Aggregate Model Structure
Mathematical Notation

\[ M \]

\[ c \]

\[ \beta \]

Fractional Prevalence

\[ \mu \]

Recovery

Immigration of Susceptibles

\[ S \]

\[ I \]

\[ R \]

\[ N \]

Immigration Rate

Incidence

Population Size

Per Contact Risk of Infection

Susceptible

Incidence

Recovered

Absolute Prevalence

Mean Time with Disease

Susceptible

Incidence

Fractional Prevalence

Population Size

Per Contact Risk of Infection

Immigration of Susceptibles

Immigration Rate

Recovery
Underlying (Ordinary) Differential Equations

\[ \dot{S} = M - c \left( \frac{I}{N} \right) \beta S \]

\[ \dot{I} = c \left( \frac{I}{N} \right) \beta S - \frac{I}{\mu} \]

\[ \dot{R} = \frac{I}{\mu} \]
Model Mathematical Analysis

System Linearization (Jacobian)

\[
\begin{bmatrix}
-\beta \text{ Infectives} - \delta \\
\beta \text{ Infectives} \\
\end{bmatrix}
\begin{bmatrix}
-\beta S - \delta \\
\mu + \frac{\tau \text{ Infectives}}{h} + \frac{\text{ Infectives} \tau}{\left(\mu + \frac{\tau \text{ Infectives}}{h}\right)^2 h} \\
\end{bmatrix}
\]

Fixed-Point Criteria

\[
\dot{S} = -c \left(\frac{I}{N}\right) \hat{S} + R\delta = 0
\]

\[
\dot{I} = c \left(\frac{I}{N}\right) \hat{S} - \frac{I}{\mu + \frac{\tau I}{h}} = 0
\]

\[
\hat{R} = \frac{I}{\mu + \frac{\tau I}{h}} - R\delta = 0
\]

Eigenvalues (e.g. for stability analysis around fixed-point)

State space diagram (reasoning about many scenarios at once)
Some Uses of Formal Approaches

- Explaining observed behavior patterns
- Identifying possible behavior modes over a wide variety of possible scenarios (e.g. via eigenspace & phase plane analysis)
- Identifying how behavior depends on parameters (stability, location of equilibria)
- Creating “self-correcting” models (via control theory)
- Formal calibration methods
Feedbacks Driving Infectious Disease Dynamics

Susceptibles

Contacts between Susceptibles and Infectives

Infectives

+ 

New Infections

New Recoveries

+ -
Example Dynamics of SIR Model (No Births or Deaths)

Susceptible Population \( S \) : SIR example people
Infectious Population \( I \) : SIR example people
Recovered Population \( R \) : SIR example people
Shifting Feedback Dominance

SIR Example

Susceptible Population S : SIR example people
Infectious Population I : SIR example people
Recovered Population R : SIR example people
Dynamic Uncertainty: Stochastic Processes

(Stochastic Differential Equations)
Stakeholder Engagement with Created Models

• Team Meetings

Mabry, 2009, “Simulating the Dynamics of Cardiovascular Health and Related Risk Factors”
Varied Applications of System Dynamics

- Aggregate population-level models
- Stratified models
- Models of an individual
- Models of interactions of two or more individuals
- Stochastic models
Key Take-Home Messages on SD

• Focuses on feedbacks as the fundamental shapers of dynamics
• Models are consciously specific to purpose
• Includes both qualitative & quantitative components
• Offers strong stakeholder focus
  • Group model building
  • Stakeholder learning laboratories
• Can be applied at diverse levels of granularity
• Models admit to formal reasoning & analysis
System Science Methodologies: Highly Complementary

- No one system science methodology offers a replacement for the others
- Significant synergies can be secured by using combinations of methodologies to address the same problem
  - As cross-checks on understanding where two or more can be applied
  - Exploiting competitive advantages
Multi-Framework Modeling

- We have found the use of multiple frameworks most effective
  - Co-evolving multiple models for
    - Cross-validation
    - Asking different sorts of questions
  - Within a single model (cf Multi-scale modelling)
- Critical that dynamic models leverage with non-dynamic modeling tools
  - Decision trees
  - Game theory
  - Biostatistical analyses
Multiple Modeling Types

System Dynamics

Agent-Based Modeling

Social Network Analysis

- Deriving calibrated parameter estimates for low-level model
- Focusing AB exploration
- Inspiring key initial structure of agent-based models
- Diagramming out high-level drivers of behaviour
- Description of continuous individual-level evolution
Network Embedded Individuals
Multiple Modeling Types

System Dynamics

Agent-Based Modeling

Social Network Analysis

Cross-validating SD aggregation
Giving insight into feedbacks to depict
Evaluating dynamic importance of stratifying to capture heterogeneities