Using PID Control for Theory Development and Policy Design: Methods and Analysis

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Intro: A control theory concept was useful for research in sustainable supply chain management

In supply chain management (SCM), system dynamics (SD) has influenced theory development and policy design. Sustainable SCM (SSCM) has received less attention (Rebs (2019)). This case used SD in to develop a multi-scale theory of SSCM (Allen (2023)).

Minorksy's (1922) idea of past, present and future values of a goal-gap as key to stability was formalized in control theory as proportional, integral, derivative (PID) control (Bennett (1993)). By "tuning" a weight for each term, nonlinearity is endogenized in a policy. Its potential for SCM is under-explored (Lin, (2017)).

This work advances the eclectic SD approach to SCM (Akkermans (2005)) in Saeed (2008, 2009) using familiar theories in SCM and SSCM.

Methods: A PID Tuning approach for SD Models

Analysis 1: PID makes a simple CLD into a suitable theory development instrument

PID helps simulation-based story-telling and conceptual theory development by making descriptive temporal concepts precise. The causal loop diagram (CLD) in the box shows where PID was used, the large CLD shows it in simulation, and the table describes the variables using related theories. Stakeholder theory (Mitchell, 1997) is used very widely in SSCM, it is advanced causally and dynamically. Emancipatory theory is perceived as the next frontier, key anomalies are addressed. PID makes commonalities across theories apparent and highlights the value of CLDs and simulation in theory development. Tuning also enables nuanced discussion of stakeholder wisdom without omniscience.

CLD segment expanded to show how PID control facilitated both the CLD-to-simulation jump and conceptual theory development (table)

Analysis 2: With good policy design, PID can resolve sustainability trade-offs

By minimizing the bullwhip effect, an appropriately designed PID policy mitigates trade-offs among its supply chain's social (discount sales and charity), **economic** (overproduction and lost sales), and **environmental** (composting and landfilling) impacts (see figure). The client uses simulation routinely and could feasibly tune controllers for its thousands of products since constants (lead time, perishability, etc.) generalize across products given adequate investment in policy design.

Lost Sales Volume per Day by Product for BCS with Alternate Transient Inputs for PID Tuning

* - BCS= Tuned for D Step, else tuned for Noise. Circle shows match of tuning to transient. BCS is the recommendations scenario (Best-Case or BCS).

At t=5, demand doubles. Is the PID controller tuned for step?
- No - sustained oscillations (**blue**)
- Yes - temporary mountain (orange)

At t=5, noise introduced. Is the PID controller tuned for noise?
- No - sustained oscillations (**green**)
- Yes - intermittent mountains (**black**)

Policy design shows PID reduces lost sales in bagels and Caesar salad and is inappropriate for Salad Onions, where a 1 day lead time makes bullwhip less important.

Discussion: Can modelers use control theory and still be doing system dynamics?

In laying out the principles for formulating system dynamics simulation models, Jay W. Forrester (1961) clearly distinguishes between information feedback and servomechanisms: problems in social systems are not unitary but are spread widely across society and the responses to them emerge in a dispersed fashion with diverse actors. Hence, control theory is unlikely to be directly useful modeling.

PID control was useful in this case study research by synthesizing conflictual ideas and showing effective insights. Control theory's rich metaphors may be more valuable than previously considered for theory-oriented research.

In addition to model-based insight, the meta-level insights showed ways managers and scholars can use system dynamics simulation. This helped to link model-based insights across time scales and to advance the research's multi-scale theory development objectives. When used in an appropriately-eclectic method, control theory can be used in system dynamics research.

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