Attacking the Communications Challenge for System Dynamics: Bringing Stock Accumulation into the Daylight

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Those most involved in System Dynamics (SD) believe it offers the power to tackle and solve a vast range of challenges throughout all fields of human endeavour. This community therefore shares a profound and continuing disappointment at the very slow uptake of SD by society at large, especially those with policy responsibility whom we seek to help. Whilst various explanations have been posited for this failure, we remain unclear as to why it continues and, more importantly, what can be done about it. Since the SD method is (to us) clearly powerful, the finger of suspicion must point towards how we communicate the method and demonstrate its power – 'If the joke is OK, maybe the problem is with the way we tell it!'

This paper explores whether the field's adoption of causal-loop diagrams (CLDs) as both an entry-point and communications device has, in spite of its intuitive appeal, been a dead end. In most popular communications of SD and its applications, CLDs have relegated the accumulation of asset-stocks to an incidental role, or even excluded this ubiquitous process entirely. Yet not only is asset-stock accumulation the true core of SD, it is also deeply fundamental to the dynamic behaviour of all social systems. This paper argues that it is not only possible, but essential, to build asset-stock accumulation back into all attempts to inform and educate others about SD, and in all communications of the insights arising from SD work.

PLEASE NOTE – this paper may be construed as critical of the efforts of many SD professionals. No such criticism is intended, and their considerable expertise and contributions are fully acknowledged. The paper's concern is, rather, directed at the need to build understanding and demand amongst non-experts.

System Dynamics has struggled to make an impact

An annual survey by Bain & Co[1] lists the most popular management tools used by management. These appear to feature a few main categories –

- simple principles, open to wide interpretation - Vision Statements, Strategic Planning,
- substantial changes to business configuration – Re-engineering, Outsourcing
- substantial changes to management processes – Value-Based Management, Balanced Score-Card
- problem-solving methods – Five Forces, Real Options, Customer Segmentation

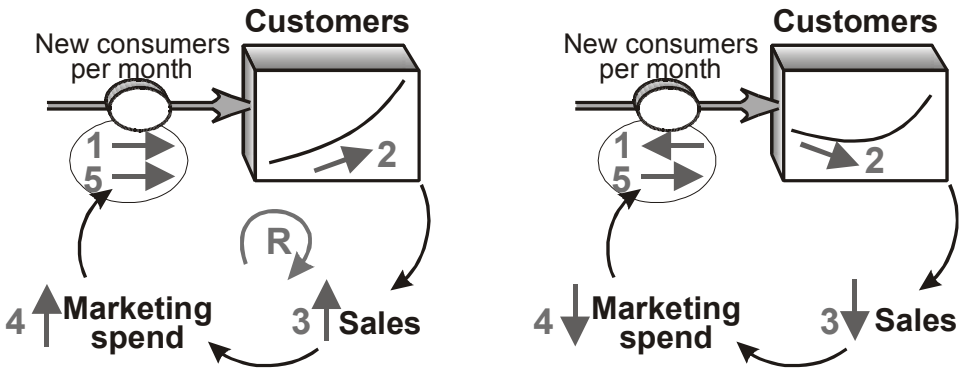
Regrettably, SD does not feature in this list, being mentioned only once in a list of some 70 concepts. This in spite of the astonishing success of The Fifth Discipline[2] in bringing systems thinking to the attention of general management and a wider public.

SD seems to fit most closely into the last of the above groups of management tools, with possible application also in the third category. The tools most widely adopted and retained in these groups appear to offer a high ratio of demonstrable value to effort required. The SD field largely accepts as axiomatic that causal loop representations of management challenges are both relatively straightforward to generate, and produce powerful and actionable insights. Yet SD's failure to establish itself amongst management implies either that little usable output arises from the laying out of qualitative feedback structures, or that the potentially more substantive guidance from simulation modelling comes at too high an input cost (or also delivers insufficient usable output)

The (further) problems with causal loop diagrams

The limitations of CLDs have been well articulated by others, and widely understood for many years[3,4]. The leading text-books in the field are explicit about these limitations – see for example Sterman, 2000, p.166[5] and Vennix, 1996, Chapter 2[6]. The technical problem arises at the flow-to-stock boundaries in feedback loops. In Figure 1, an initial increase in customer acquisition rate results in reinforcing processes that drive further growth. However, a *decrease* in customer acquisition (or indeed an actual loss of customers) merely slows, temporarily, the growth in customers through time.

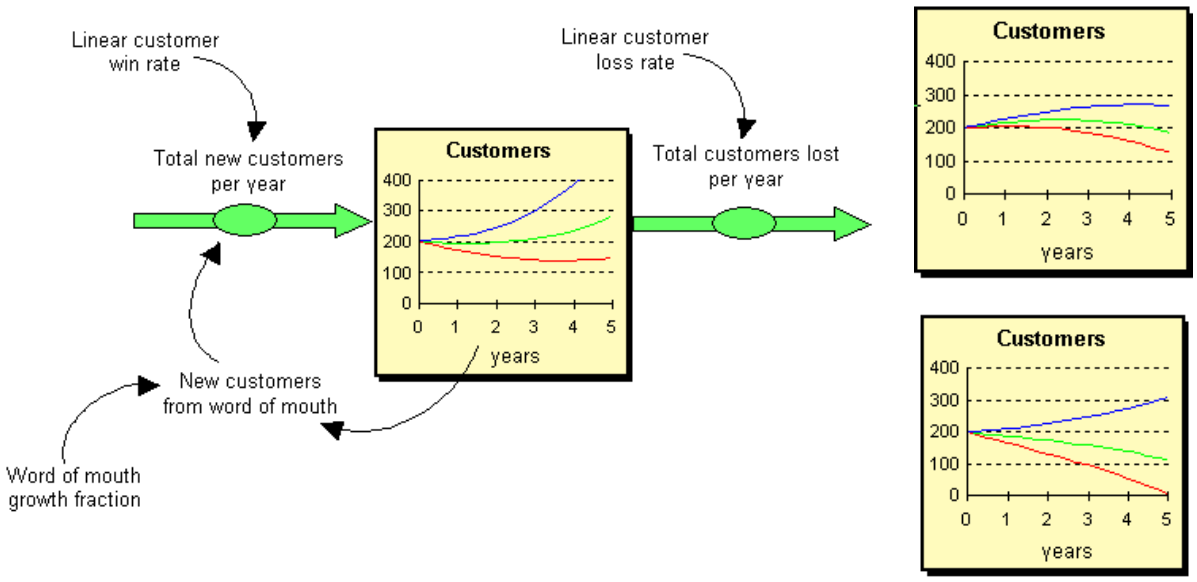
Figure 1: Reinforcing feedback with no mechanism for decline.



A common get-out to this awkward behaviour of accumulating stocks in feedback structures is to assert that the decline in the flow-driver (here, the drop in marketing spend) causes the stock (customers) to be lower *than it otherwise would have been*. However, this does not solve the problem that the stock's value is still *higher* than it was in the previous period. The author's experience has been that this observation completely mystifies newcomers to system dynamics, and destroys their faith in the simplicity of reinforcing and balancing feedback that may have been built up beforehand.

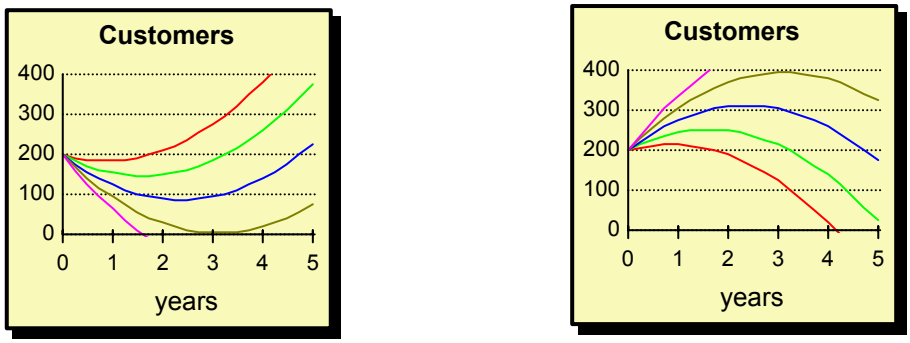
A further problem arises when we add to this structure an additional *linear* flow – i.e. in- or out-flows that are either constant, or else that grow or decline in a straight-line. The time charts in Figure 2 all result from the addition of a linear flow to a single reinforcing loop.

Figure 2: Varieties of behaviours from reinforcing feedback plus linear flows.



Similar problems arise with balancing feedback. The goal-seeking behaviour commonly ascribed to this structure can readily be changed into a wide variety of time-paths, if linear flows are also taking place. Furthermore, the interactions of linear flows *alone* is quite capable of generating complex behaviour (in the sense that resulting time paths for stocks are not intuitively obvious). The left-hand charts in Figure 3 arise from a variety of out-flows from the customers stock, plus a constantly rising in-flow – *with no feedback.* The right-hand set of time-paths arises from the opposite combination – a variety of in-flow rates plus a linearly rising out-flow. This complexity can become still more severe when resources flow through two or more stocks, for example as staff develop through junior and senior levels, with promotion and attrition at both stages.

Figure 3: Varieties of behaviours from interacting linear flows, and no feedback.



Linear flows are not only plausible, but quite common when viewed over the time-scale of real managerial challenges – a rival's unchanging sales force can capture our customers at a constant rate, a retailer's linear growth of stores can accumulate straight-line growth in numbers of customers served, and so on. Yet such flows into and out of the model-boundary rarely appear in published CLDs for problem situations, nor do SD texts typically devote attention to how they should be identified and represented.

The conclusions from these considerations are stark:

- feedback is neither necessary nor sufficient to cause complex time-paths in resource-stocks, and
- we can neither confidently give the causal structure that gives rise to any time-path, nor give the time-path that will arise from any feedback structure.

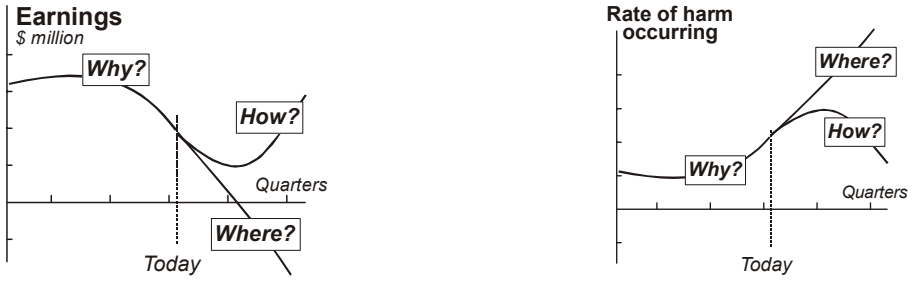
In addition, real-world resource-flows, with no involvement in any feedback relevant to a situation, can have powerful, even overwhelming, influences on system behaviour, yet are commonly ignored in CLDs. These unavoidable flaws in the core building block of causal-loop diagrams fatally damages their claim to constitute 'shared mental models', from which groups of individuals can agree on both the diagnosis and prognosis of a situations, as well as on prescriptions for performance improvement.

The consequences in practice that arise from these problems are well-understood. No two groups, set to diagnose the same problem, will reliably generate the same feedback diagram. Consequently, there is little likelihood that they will arrive at comparable interpretations of its behaviour, or policy recommendations for its improvement. Furthermore, any SD models that are written to simulate the situation-behaviour will be highly contingent on the diagram that the group happened to develop, giving little confidence in their quantitative findings. This unreliability gives rise to the caution frequently issued – that only experienced SD professionals can reliably coach a team through the construction of a CLD for their situation. Given the extremely small number of such experts, we appear to have an explanation for the failure of SD to achieve significant reliable adoption amongst management.

Managerial concern is with the *scale* and *trajectory* of their situation

A thorough reconstruction of SD's communications with other communities, especially those with leadership responsibility, requires that we return to the fundamental questions they need answered. A generic form in which managerial challenges can be expressed is the 'performance through time' chart (Figure 5). Although feedback systems analysis commonly notes such performance charts at the outset, the process often 'parks' them whilst a qualitative causal diagnosis is completed. Yet this setting aside of the quantitative, time-based representation of the problem-situation makes precisely the assumption that is known to be false – that causal structures can be inferred from time-paths of behaviour. These challenges, as they concern those actually involved with them, feature both *quantity* and *timing* – policy-makers need to know *why* these measures are at their current scale, and moving on their current trajectory, *where* they are heading and at what speed, and lastly *how* policy responses might alter this trajectory for the better. Since these starting questions are always, at least implicitly, quantitative, any useful answers must also be quantitative – policy-makers need to know what to do, when and how much, and with what likely impact on the scale and trajectory of the system's behaviour through time.

Figure 5: Performance-through-time challenges in commercial and non-profit examples



Problems with regression methods in empirical analysis

In the absence of good system dynamic analysis of such problem situations, the most widely used tool, at least in empirical management research, as well as in other social sciences, is multivariate regression analysis. Profitability might be found, for example, to be correlated with the number of rival firms, or the relationships between senior managers, and social harm (such as civil conflict) might correlate with GDP growth, or educational levels. Yet there are serious flaws in the use of such approaches.

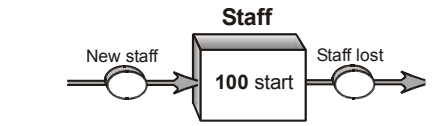
First, they commonly ignore known, strong arithmetic dependencies. In business performance, for example, profitability is already *entirely* explained by the factors from which it is calculated – i.e. the line-items in the profit and loss account. This arithmetic provides 100% explanation for the dependent variable, with no remaining error term. In civil conflicts, the casualty rate is much more immediately explained by the number of combatants and weapons than by macro-economic factors.

The fatal flaw in the use of regression methods in social sciences arises from the fact that this causal arithmetic *always* traces back, eventually, to one or more accumulating stocks (known, in management situations, as 'resources' such as customers, staff or capacity). The stock and flow behaviour of these factors, the central theoretical notion of SD, makes meaningless the use of simple regression methods in any attempt to explain the quantity of an asset-stock. *The current quantity of every asset-stock is not 'correlated' with anything – it is, at all times, past, present and future, identically equal to the sum of everything ever added, minus everything ever lost (Figure 6)*. This is not an opinion, theory or coincidental discovery from empirical research. It is an unavoidable feature of reality – a law of nature.

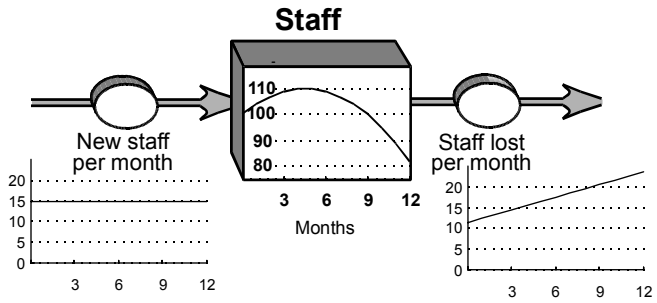
In such processes, all of history matters. For example, a customer won yesterday is (*ceteris paribus*) exactly as relevant to today's sales rate as a customer won 10 years ago. Consequently, the *causes* of that acquisition yesterday is exactly as relevant as the causes of the acquisition 10 years ago. This means that

it is equally meaningless to seek statistical relationships with *delayed* causes (today's customers are not explained by price or marketing 3 months ago)

Figure 6: Explaining the level of a resource, through time.



Jan	+15 per month	**104** (end)	-11 per month
Feb	+15	**107**	-12
Mar	+15	**109**	-13
Apr	+15	**110**	-14
May	+15	**110**	-15
Jun	+15	**109**	-16
Jul	+15	**107**	-17
Aug	+15	**104**	-18
Sep	+15	**100**	-19
Oct	+15	**95**	-20
Nov	+15	**89**	-21
Dec	+15	**82**	-22



The further, unavoidable implication is that, if regression analysis cannot explain usefully the current quantity of any asset-stock, then it is also impossible to explain any value that *depends upon* that asset stock, which in management situations includes all financial performance measures. There is thus no possibility that strategic rules, guidelines, theories or frameworks built on regression analysis can offer more than a passing, coincidental resemblance to reality.

It should be noted, at this point, that the relationships depicted in Figure 6 are well within the capacities of most people with a sound general education to cope with. That is not to say that they can intuitively estimate time-paths for asset stocks from any set of in- and out-flows, but most individuals can readily work through the numbers in such cases. This implies that one of the principal purposes of CLDs – to obviate the need for people to understand stock-and-flow relationships – was not only an inappropriate objective, but also unnecessary.

Bringing asset-stock accumulation to the explanation of dynamic behaviour

The problems of correlation analysis in empirical research can be illustrated with an example of the customers, sales and profits of a simple firm (Figure 7). Customers are won, with no delay, by marketing spend – the more marketing, the faster they are won. The same marketing spend also encourages customers to buy more. A constant fraction of customers is lost each month. The firm's monthly revenue is calculated from the rate of units sold per month, multiplied by the unit price, and monthly earnings reflect this revenue, minus certain fixed and variable production costs and the marketing spend.

Figure 7 shows a specific performance scenario that arises when this firm follows a particular history of marketing spend. It illustrates, incidentally, a further flaw in the use of qualitative CLDs as means of explaining the time-path behaviour of problem situations. The future trajectory of the system's performance depends not only on its causal structure, but also on the *current, quantified state and trajectory* of all its components.

Figure 8 shows the plots of both revenue and earnings vs. marketing spend. Each X corresponds to a single month's results. These plots show why correlation will fail to support any plausible hypothesis for the relationship between dependent variables (revenues or profits) and the independent variable (marketing spend). For any new *static* rate of marketing spend, the firm's revenue and earnings start *moving* along a new trajectory. Where that trajectory starts and ends depends on both the starting point and the period over which the new spending rate is continued.

Figure 7: Revenue and earnings over time reflecting customer acquisition from marketing only.

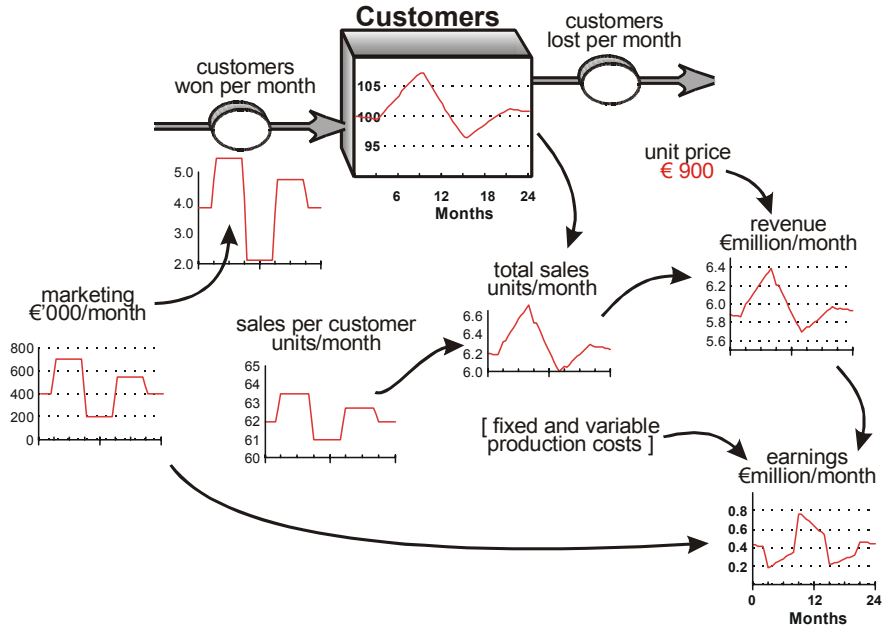
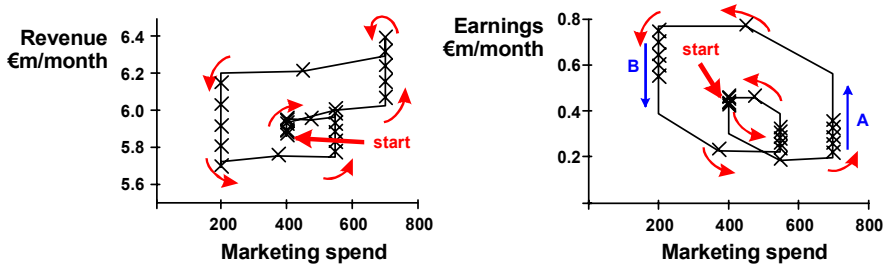


Figure 8: Misleading relationship between revenue, earnings and marketing spend.



During months 3 to 9, earnings are low, but only because of low historic marketing spend, *and* because spend has just increased by €300,000/month. Earnings then start increasing along path A, but in month 10, suddenly jump to a much higher rate, simply because the firm cuts its marketing spend. The apparent relationship between higher marketing and lower earnings, then, is entirely illusory. Had the high marketing of period A continued, earnings would, within a few months, have surpassed the earnings rate at the end of period B.

Generalising from this illustration, it is apparent that *regression methods will be irreparably unsafe whenever an asset-stock exists between a variable to be explained and any hypothesised causal factor*. The true theoretical core of SD – stock accumulation - offers a much more powerful basis for a theory of strategic performance …

1. *The performance of the enterprise, Π, at time T depends on the levels of strategic resources R_1 to R_n, on discretionary management choices, M, and on exogenous factors at that time E* - Equation 1. (Note that those exogenous factors themselves include accumulating stocks.)

$$(1) \qquad \Pi(T) = f\left[R_1(T),..,R_n(T),M(T),E(T)\right]$$

2. *The current level of resource R at time T is the sum of its net rates of accumulation r since time t=0*, plus its initial quantity (Equation 2).

$$(2) \qquad R_i(T) = \int_0^T r_i(t)dt + R_i(0)$$

3. *The current rate of accumulation r_i of resource i at time T is a function of the current level of all existing resources, including that of resource i itself, on management choices, M, and on exogenous factors E* (Equation 3).

$$(3) \qquad r_i(T) = f_i\left[R_1(T),..,R_n(T),M(T),E(T)\right]$$

Note that equations 1 and 3 need imply only simple, linear causality. Since such causal relationships are already amenable, in practice, to arithmetic derivation or statistical testing, the *unique* contribution of SD to any theory of performance in social systems arises from its capture of stock-accumulation processes. Feedback structures are thus artefacts that arise from this theoretical core – they are not in themselves, 'the theory'.

Conclusions

This brief note has sought an explanation for the failure of SD to gain any sustained traction amongst management. It appears that the use of CLDs in education and practical application, whilst well-intentioned has contributed little, and may indeed have positively obstructed, progress towards this aim. This is not to criticise at all the highly skilled and dedicated efforts of the many expert SD professionals. Rather, it is an inevitable consequence of the theoretical, managerial and pedagogical flaws embedded in the approach.

Stock accumulation is the truly fundamental building-block of SD, with feedback merely a widespread, and of course important, consequence of that core theory. Stock-and-flow analysis, complete with quantitative time-path portrayal of all important system variables (*especially* of the stocks and flows themselves), cannot be avoided if any confidence is to be had in the diagnosis, prognosis and policy-response to real-world challenges. Furthermore, this task is not beyond the capabilities of reasonably-educated professionals to carry out, given sound tuition. Very many real-world challenges arise from the dynamic behaviour of just one stock, so the SD profession may conceivably win some new understanding and commitment from its audience by helping them tackle such challenges, before moving on to the considerable complexities of wider system structures.

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[1] Bain & Co, 2001, 'Management Tools Global – 2001', www.bain.com

[2] Senge P M (1990) *The Fifth Discipline.* New York: Doubleday

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