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System Dynamics in Six Sigma Practice

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System Dynamics (SD), like Six Sigma, is concerned with improving performance through time. Building on the Strategy and Tactics of Six Sigma from Eckes (2001), SD from Sterman (2000), and strategy dynamics (SD as applied to strategy development) from Warren (2002), this paper suggests several roles for SD in both strategic and tactical Six Sigma practice (see Table 1).[1] *The primary thesis of the paper is that system dynamics is an appropriate Six Sigma tool when the problematic behavior being addressed by the Six Sigma project may be arising from feedback structure. This thesis is illustrated using an example from High Performance Systems, Inc.*

Keywords: six sigma, DMAIC, system dynamics, strategy, strategy dynamics, business strategy, business process modeling, business process improvement

Introduction

Eckes (2001) defines the "Strategy of Six Sigma" as a Business Process Management (BPM) strategy that encompasses the tactical Six Sigma DMAIC steps shown in the first column of Table 1.

Three guiding principles seem evident from Eckes' Strategy of Six Sigma in the first column of Table 1:

1) All business processes should be identified and quantitatively managed, that is, controlled and improved (Process Owners and Green Belts, supported by Master Black Belts).

2) Business processes whose improvement is most important to achieving strategic business objectives should be selected for focused process improvement using the firm's best process improvement resources (e.g. Process Improvement Teams, facilitated by Black Belts, and supported by Master Black Belts)

[1] *Readers unfamiliar with SD or Six Sigma may glean some idea of the basics from, respectively, Appendix 1, and the first column of Table 1. Likewise, some idea of the basics of strategy dynamics, the application of SD to business strategy, may be gleaned from Appendix 2 and Appendix 3. See StewardshipModeling.com for more background on SD, StrategyDynamics.com for more on Strategy Dynamics, and iSixsigma.com for more on Six Sigma. Readers please note that, although this paper is intended for a Six Sigma audience, the author is much more familiar with SD than with Six Sigma.*

3) Items 1 and 2 above should be continuously managed as the business environment and strategic business objectives change over time.

System dynamics (SD) can contribute to Six Sigma practice as summarized in the 2nd column of Table 1, and as more thoroughly described in the sections following Table 1. Table 1 can be viewed as an executive summary of this paper.

Strategic Six Sigma Roles for SD

Quantifying the Selection of Strategic Six Sigma Projects

Strategic Six Sigma projects are those projects to which the firm dedicates its best Six Sigma resources. Six Sigma strategic project selection criteria generally include some form of *qualitative* weighting of candidate processes to determine their anticipated contribution to the achievement of strategic business objectives.[2] For example, Eckes (2001, pages 26-27) recommends that managers go through a *qualitative* voting process to weight candidate processes. Other Six Sigma texts recommend similar qualitative approaches.[3]

Six Sigma practice can be improved by making project selection more *quantitative*. Strategy Dynamics, an application of SD, offers *quantitative* development of competitive business strategy, as determined by consideration for firm and competitor resources, capabilities, and business processes. It is Strategy Dynamics' consideration of business processes that creates a role for SD in strategic Six Sigma practice.

Thinking of business objectives as preferred time paths of business performance, SD offers three contributions to the process for selection of strategic Six Sigma projects. First, the act of building a strategic architecture (Appendix 2) requires managers to be more specific and quantitative than they probably otherwise would be in their thinking about how the time path of outputs from each business process relates to achieving each business objective. Second, the strategic architecture can easily be simulated on a computer to help managers quantitatively improve their thinking about how the outputs from firm processes interact to achieve a set of specific strategic business objectives. Third, simulation allows the strategic architecture to be quantitatively tested for sensitivity to uncertainties both within the firm itself, and within its environment, thus providing yet more information to improve management thinking about which process projects the firm should commit its best Six Sigma resources.

[2] Eckes (2001) gives an example of selection criteria for first Six Sigma projects. Eckes' criteria include the degree to which a proposed process improvement project addresses strategic business objectives, the current process performance relative to desired process performance, and feasibility considerations (degree of difficulty, use of resources, time commitment).

[3] See Breyfogle (2001), Brue (2002), Chowdhury (2001), George (2002), Harry (2000), Pande (2000), and Pande (2002).

The Strategy of Six Sigma, from Eckes (2001), p13[4]	**Suggested SD Roles in Six Sigma practice.**
Eight Essential Steps in Business Process Management (BPM), p15	
Step 1 Creation and Agreement of *Strategic Business Objectives*, p16	Quantifying the selection of strategic Six Sigma projects Setting process output targets that are causally and quantitatively linked to strategic firm performance over time
Step 2 Creation of *Core, Key Sub-, and Enabling Processes*, p17	
Step 3 Identification of *Process Owners*, p20	
Step 4 Creation and Validation of *Measurement "Dashboards,"* p21 4a) *Effectiveness* (process output) dashboard measures. 4b) *Efficiency* (internal process) dashboard measures.	
Step 5 *Data Collection* on Agreed Dashboards, p24	
Step 6 Creation of *Project Selection Criteria*, p25	
Step 7 Choosing *Projects* (both first projects, and later projects),p25	
The Tactics of Six Sigma – *DMAIC*, p34	
7a) *Define*. Define the customers, their requirements, the team charter, and the key process that affects that customer. Chap 4, p41	Another form of process map useful when feedback causality is present.
7b) *Measure*. Identify the key measures, the Data Collection Plan for the process in question, and execute the plan for data collection. Chap 5, p69	Selecting variables for focused data collection when feedback causality is present.
7c) *Analyze*. Analyze the data collected as well as the process to determine the root causes for why the process is not performing as desired. Chap 6, p111 & Chap 7, p139.	Finding the root cause of common or special cause variation[5] when feedback causality is present.
7d) *Improve*. Generate and determine potential solutions and plot them on a small scale to determine if they positively improve process performance. Chap 8, p173.	Determining potential solutions when feedback causality is present.
7e) *Control*. Tactical Control - Develop, document, and implement a plan to ensure that performance improvement remains at the desired level. Chap 9, p205.	Tracking and controlling process output when feedback causality is present.
Step 8 Strategic Control – *Continual Management* of Processes to Achieve Strategic Objectives of the Organization, p231.	Tracking & controlling process output contribution to firm performance over time

Table 1: The "Strategy of Six Sigma" from Eckes (2001), and where and how system dynamics (SD) can contribute to Six Sigma practice.

[4] Note that other Six Sigma authors, e.g. Pande et. al. (2000) recommend two-tiered Six Sigma processes that are comparable to Eckes' (2001) 'Strategy' and 'Tactics' tiers in Table 1. See Appendix 5 for an overview of Pande's two-tiered Six Sigma process.

[5] See the section entitled Common or Special Cause Variation (best read after reading the Analyze and Improve sections of this paper).

Setting Process Output Targets that are causally and quantitatively linked to strategic firm performance over time

Simulation of the strategic architecture as mentioned above has yet more strategic benefits. Simulation reveals the approximate[6] time paths of each process' outputs required to achieve the preferred time paths of firm performance (the business objectives). These approximate process output time paths can be used to provide process owners with targets and ranges for process outputs over time, which targets and ranges are better defined than they otherwise would be. Further, the strategic architecture and its simulation can provide process owners with an explicit quantitative understanding of not only the causal linkages from their process outputs to the expected time paths of firm performance, but also of how interplay among all the firms' processes can affect the time path of firm performance. Such understanding can improve collaboration among process owners and others toward maximizing firm performance through time.

Tracking & controlling process output contribution to strategic firm performance

Process output time paths from strategic architecture simulations also give firm management a way to track process output performance at every Quality Council meeting.[7] Should actual process output performance differ from desired (simulated) process output performance, simulation of the strategic architecture enables firm management to anticipate the effects of these differences on the time path of firm performance (the business objectives). A choice can then be made to either revise expectations on the time path of firm performance, or to dispatch Six Sigma process improvement resources to address the process performance problem.

Both Eckes (2001, pages 232-234) and Warren (2002, pages 276-279) discuss the use of balanced scorecards for, respectively, business process management and strategic control. Warren notes that strategic architecture simulations can be useful in creating balanced scorecards for the firm. He writes:

"*Integrating a sound strategic architecture with Balanced Scorecard principles leads to a scorecard that is not only balanced but compact, joined up, and dynamically sound.*"

Further, strategic architecture simulations can be incorporated into a 'dynamic' balanced scorecard for the firm developed using SD. There is a growing recognition of the value of dynamic balanced scorecards as compared to traditional scorecards. David Norton and

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[6] 'Approximate' because SD deals with the time path 'tendencies' of systems as described in Meadows (1985), "System dynamicists are not primarily concerned with forecasting specific values of system variables in specific years. They are much more interested in general dynamic tendencies; under what conditions the system as a whole is stable or unstable, oscillating, growing, declining, self-correcting, or in equilibrium."

[7] Eckes (2001, page 231) describes the Business Quality Council as being "comprised of the business leader and his or her direct reports and any nonmanagement process owners…It is the job of the Business Quality Council to continually manage progress toward achievement of the business process goals and to maintain the integrity of the Six Sigma initiative."

Bob Kaplan, the popularizers[8] of the balanced scorecard, have written about the importance of considering dynamics in the development and use of balanced scorecards:

Bob Kaplan and I have long believed that Dynamic Systems Simulation would be the ultimate expression of an organization's strategy and the perfect foundation for a Balanced Scorecard… Our fondest hope is that, when the history books are written, it will be said that strategy maps and Balanced Scorecards were the Trojan horses that made System Dynamics a standard tool of management."
(Norton, 2000 and Richmond, 2001)

High Performance Systems (2001) and 2000 provide software demonstrations of the development and application of dynamic balanced scorecards. There is a growing body of literature relating to the ***dynamics*** of performance measurement, ***dynamic*** decision-making, and ***dynamic*** balanced scorecards. References are listed in the Dynamic Balanced Scorecard References section at the end of this paper.

Tactical Six Sigma (DMAIC) Roles for SD

SD's Analyze and Improve roles will be described prior to SD's Define, Measure, and Control roles because it is important to first describe feedback causality, which is most easily developed in the context of Analyze and Improve.

Analyze

Six Sigma distinguishes among the:

1) *outputs* of a process (= Customer NEEDS; see Appendix 4), and

2) customer-related *output measures* (characteristics that determine whether the customer is happy with the outputs provided = Customer REQUIREMENTS; again see Appendix 4).

Six Sigma further distinguishes among output measures, process measures, and input measures[9] as shown in Table 2.

Input Measures (Supplier Effectiveness)	Process Measures (Your Efficiency)	Output Measures (Your Effectiveness)
The key quality measures placed on your supplier	Measures of your process efficiency: ▶ Cycle time ▶ Cost ▶ Value ▶ Labor	Measures of how well you are meeting (and hopefully exceeding) your customers' requirements.

Table 2 Areas requiring measurement (Note: Table 2 is from Figure 5.1 on page 71 of Eckes (2001).)

[8] See a history of the balanced scorecard at http://www.schneiderman.com/.
[9] Eckes (2001) pages 71, 51 and 60-65.

The role of SD in tactical Six Sigma, as with other DMAIC tools, can be on either:

1) ***input measures***, ***process measures***, or ***output measures***, hereafter abbreviated to "***IPO measures***," or

2) The design or improvement of the firm's processes such that they produce the approximate[10] process output time paths necessary to create preferred firm performance time paths. See the second strategic Six Sigma role for SD.

Feedback Causality: In traditional Six Sigma practice, the variability in each IPO measure is represented as a function of some number of Xs, that is, $Y = f(X_1, X_2, X_3 \ldots X_n)$ where Y is the IPO measure. Each X is typically thought of as belonging to one of six groups referred to as "5Ms and 1P" (Mother Nature, Machine, Materials, Methods, Measurement, and People).[11] The focus of the DMAIC analysis phase is to find the "root causes" (the Xs) that create undesirable variation in Y. Statistical techniques such as correlation and designed experiments are typically used to identify which Xs are causing variation in Y, and the relative influence of each X on that variation. To be valid, most of these statistical techniques require one-way cause-effect relationships. Sometimes, however, cause-effect is not one-way, but circular. In these cases, it is not the Xs that cause variation in Y, but rather the interactions among the circular feedback relationships among the Xs, and between some or all of the Xs and the Y, that cause variation in Y. It is for these cases that SD can serve a useful role in Six Sigma practice. In these cases, the cause of the undesirable variation in Y is not a set of Xs, but rather is the feedback structure of the system, that is, the interactions among the collection of feedback loops involved in the system. This cause for variation in Y is hereafter referred to as **feedback causality**.

Feedback Causality Example: The best way to understand feedback causality is with an example. High Performance Systems, Inc. (2001) (hereafter called HPS) provides an excellent example included with its ithink® Version 7 demonstration freely downloadable from http://www.hps-inc.com. The example is the model file named 'Supply chain reengineering.ITM." The reader is strongly encouraged to download and install this ithink demonstration and run this model file. The following is an overview of the HPS example, using several of its screens, beginning with Figure 1. Following the overview, feedback causality is discussed in the context of the HPS example.

Define the Problem The text in Figure 1 notes that the retailer believes the swings in inventory create unnecessary overstock costs when high, and lost sales when low. And lost sales hurt the retailer both directly through loss of revenue and indirectly through loss

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[10] 'Approximate' because SD deals with the time path 'tendencies' of systems as described in Meadows (1985), "System dynamicists are not primarily concerned with forecasting specific values of system variables in specific years. They are much more interested in general dynamic tendencies; under what conditions the system as a whole is stable or unstable, oscillating, growing, declining, self-correcting, or in equilibrium."

[11] Eckes (2001) page 133.

of customers due to poor product availability. These are certainly appropriate problems for the Six Sigma DMAIC process. We might imagine inventory management to be a sub-process of the firm's order fulfillment process.

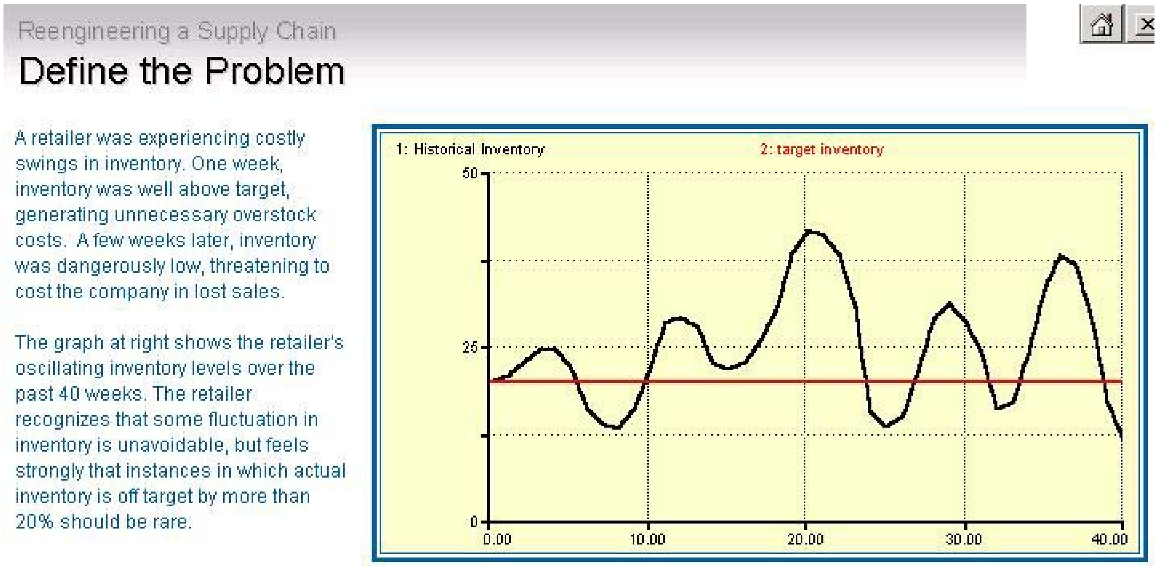

Figure 1: Define the Problem

<u>Model the As Is</u> To begin the investigation, the demonstration then investigates the As-Is environment relative to those things that influence inventory. First describing As-Is environment, the demonstration explains, "…the central piece of the "As-Is" was the firm's supply chain. That simplified chain can be described in words as follows…

"*The retailer receives orders from customers, and in turn ships them product if it's in stock. If they are out of stock, they backlog the orders until they can fill them. Inventory is re-stocked by ordering from a wholesaler. Deliveries from the wholesaler then arrive about 2 weeks after the order is picked*."

The demonstration then builds up a map of the As-Is environment as shown in Figure 2. For a detailed explanation of the map, download, install, and run the demonstration. However, one feature of the map figures prominently. From the demonstration:

"The retailer restocks its inventory from a wholesaler using an ordering policy that has two components. The first component of the retailer's ordering policy is order a volume sufficient to cover the volume of product that is being delivered to customers. The second component of the ordering policy is to boost order volumes (above delivery volumes) when inventory levels fall below target levels, and to cut back order volumes (below delivery volumes) when inventory levels are in excess of target."

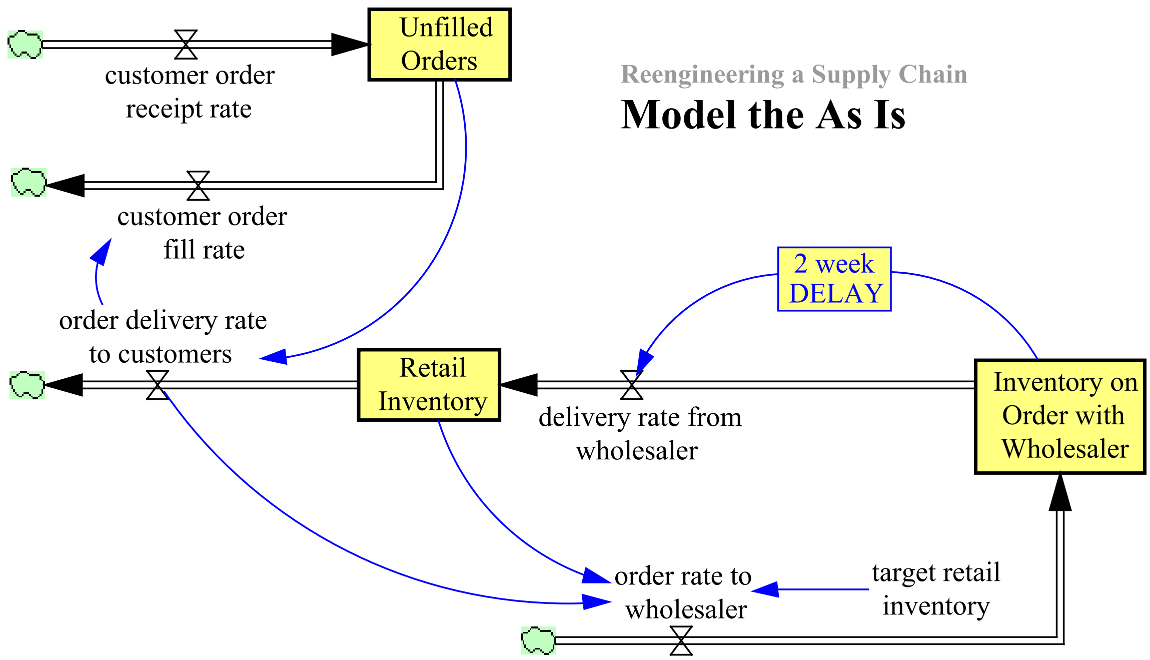

Figure 2: Model the As Is

Ordering Policy. In the As-Is SD model graphically represented in Figure 2, the ordering policy (ordering rule, decision rule) is represented in an equation for *order rate to wholesaler* as follows:

Order rate to wholesaler = F(*order delivery rate to customers, Retail inventory, target retail inventory*)

<u>Test the As Is Model</u> The demonstration then tests the structure in Figure 2 to see if it can produce behavior similar to that in Figure 1. The model is initialized in dynamic equilibrium and then perturbed by a step increase in the *customer order receipt rate.* The result of this test is shown in Figure 3.

The text in Figure 3 below states that the model-generated pattern pretty closely matches the historically observed pattern. What this means is that the amplitudes and periods of the oscillations for the model-generated and historically observed cases are reasonably close. This behavioral similarity, along with structural realism of the stock flow map of Figure 2 to the retailer's business (its "face validity"), begets confidence in the model as a possible explanation for the undesirable behavior.

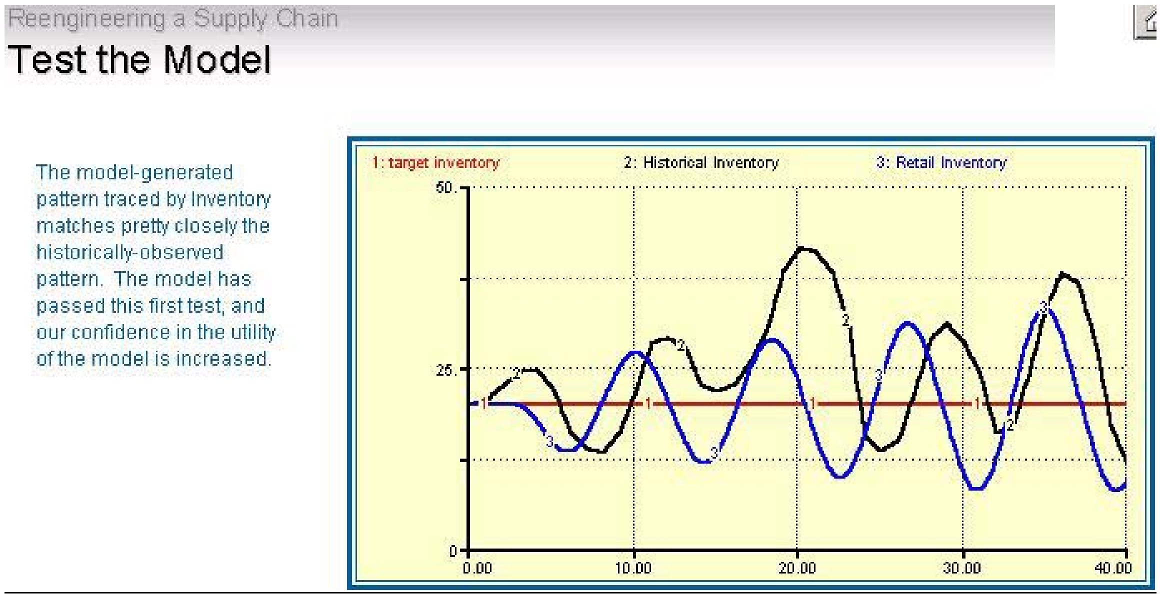

Figure 3: Test the Model

<u>Identify the Cause:</u> From the demonstration:

"*After agreement that the model has 'As Is' face validity, the next step is to use the model to develop a clear understanding of the cause of the oscillation.*

"Inventory instability is often blamed on external causes. Fingers are typically pointed in two directions: at suppliers and at customers.

"For example, a retailer experiencing inventory instability might blame wholesalers for failing to make regular or consistent deliveries. In this model wholesalers are extremely regular (i.e., their delivery time is a constant two weeks), and therefore cannot be the cause of any instabilities being experienced.

"Looking to customers, retailers may claim that incoming demand is erratic. In this model, the incoming demand stream is constant, except for one step-increase that occurs. To determine whether the oscillation in inventory being experienced is due to the magnitude of this step we can run a sensitivity analysis."

Failure of wholesalers to make regular or constant deliveries and *erratic incoming demand* are examples of Xs that might be hypothesized to create *inventory instability*, a Y, in the equation Y=f(Xs), in the traditional DMAIC process discussed earlier. Holding *wholesaler delivery time* constant at two weeks, the demonstration then uses the model to test the degree of sensitivity of *inventory instability* to different magnitudes of step variation in *incoming demand*. The results are shown in Figure 4.

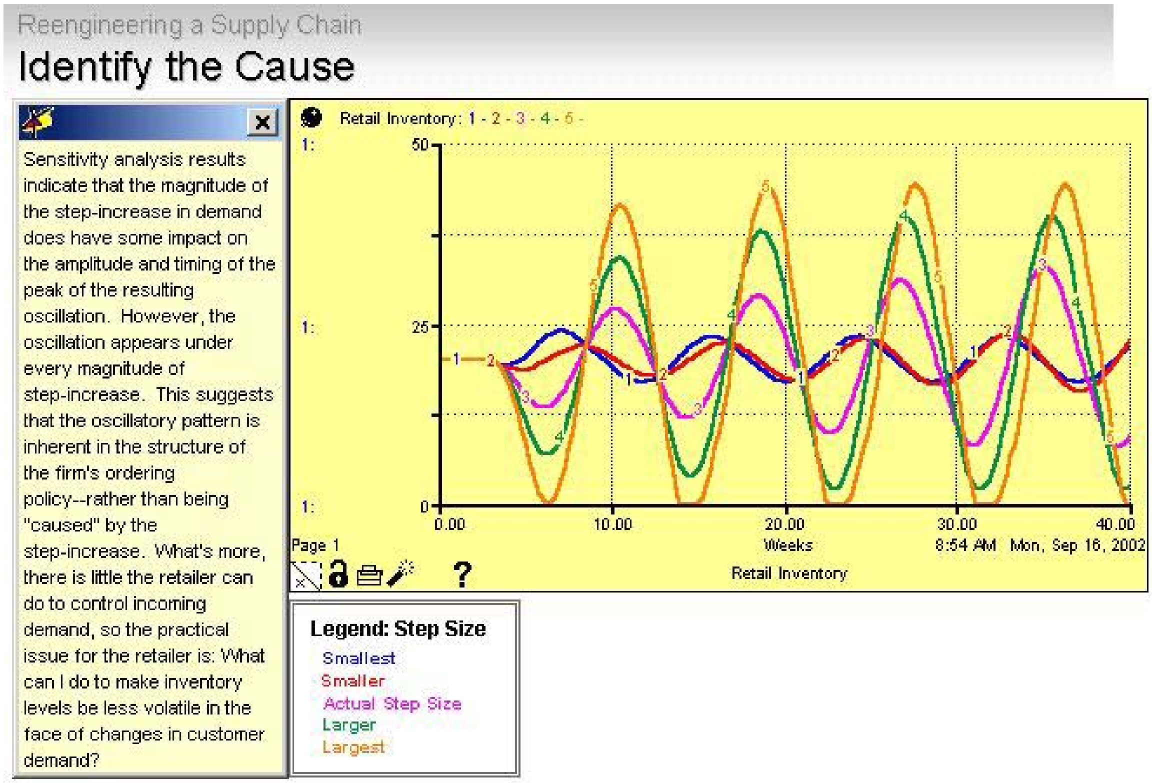

Figure 4: Identify the Cause

The text in Figure 4 is very important, but perhaps difficult to read. So, repeating it:

"*Sensitivity analysis results indicate that the magnitude of the step-increase in demand does have some impact on the amplitude and timing of the peak of the resulting oscillation. However, the oscillation appears under every magnitude of step-increase. This suggests that the oscillatory pattern is inherent in the structure of the firm's ordering policy – rather than being 'caused' by the step-increase. What's more, there is little the retailer can do to control incoming demand, so the practical issue for the retailer is: What can I do to make inventory levels be less volatile in the face of changes in customer demand?*"

This question is addressed in the next step in the demonstration – Reengineer.

Reengineer The "reengineer" step, under a flat demand scenario (a single demand step with no randomness), first describes the current and two proposed decision rules for determining the *order rate to wholesaler*. Then, continuing under the second decision rule, it again investigates the response of the system to a single step in the customer order stream, but this time with randomness added to the single step order stream. Descriptions of the current policy, the two proposed rules, and the two demand streams follow:

Current Ordering Policy: (see Figure 5 button on left side, halfway down) Looking back at Figure 2**Error! Reference source not found.**, note that *order rate to wholesaler* as a function of both *order delivery rate to customers* and the gap between *Retail Inventory* and *target retail inventory.* This reflects the two components of the retailer's current order policy. The first component is to order to replace product that is being delivered to customers – order to replace demand. In Figure 2 this is reflected in the link from *order delivery rate to customers* to *order rate to wholesaler*. The second component of the current ordering rule is to order to make up for any shortfalls, or excesses, in inventory. In Figure 2this is reflected in the links from *Retail Inventory* and *target retail inventory* to *order rate to wholesaler.*

Order More Aggressively – The 1st Proposed Reengineered Decision Rule: (see Figure 5 button on left side, halfway down). From the demonstration:

"*The logic of this ordering rule is very similar to the current policy. The 'order more aggressively' policy also orders to replace deliveries as well as adjusts ordering to cover inventory shortfalls and overages. The difference is that the retailer will respond more aggressively to any discrepancies between actual and target inventory levels. Essentially, rather than taking a 'wait and see' attitude, the retailer will jump right on any inventory shortfalls or overages by adjusting order volumes either upward or downward.*"

Consider Order Backlog - The 2nd Proposed Reengineered Decision Rule: (see Figure 5 button on left side, halfway down). From the demonstration:

"*The final ordering rule also orders to replace deliveries, as well as adjusts for inventory shortfalls and overages. Additionally this policy takes into consideration the backlog of product on order with the wholesaler. The previous ordering rules have not factored into consideration the backlog of product that is 'on order with the wholesaler' (i.e., in the pipeline to be delivered, but has not yet arrived). This ordering rule adds this 'on order' correction by subtracting what's in the pipeline from the volume being ordered (thereby preventing over-ordering).*

This ordering rule could be graphically represented in Figure 2 by adding an additional link from *Inventory on Order with Wholesaler* to *order rate to wholesaler*. This link is shown in Figure 8.

Flat Demand: (see Figure 5 button - left side, toward bottom). From the demonstration: "*Under 'Flat Demand' the simulation runs without minor, random fluctuations added to the 'idealized' customer demand stream (which is a one-time step-increase).*"

Add Randomness: (see Figure 5 button on left side, toward bottom). From the demonstration: "*Selecting 'Add Randomness' will add minor fluctuations to the customer order stream. The fluctuation will not obscure the general demand trend, but will generate a more realistic customer demand stream*."

In Figure 5, the current and both proposed decision rules are first run under a flat demand scenario [Lines labeled 1 (blue), 2 (red), and 3 (pink), respectively]. Then the 2nd proposed reengineered decision rule ‘Consider Order Backlog’ is run under the ‘Add Randomness’ demand scenario [Line labeled 4 (green)].

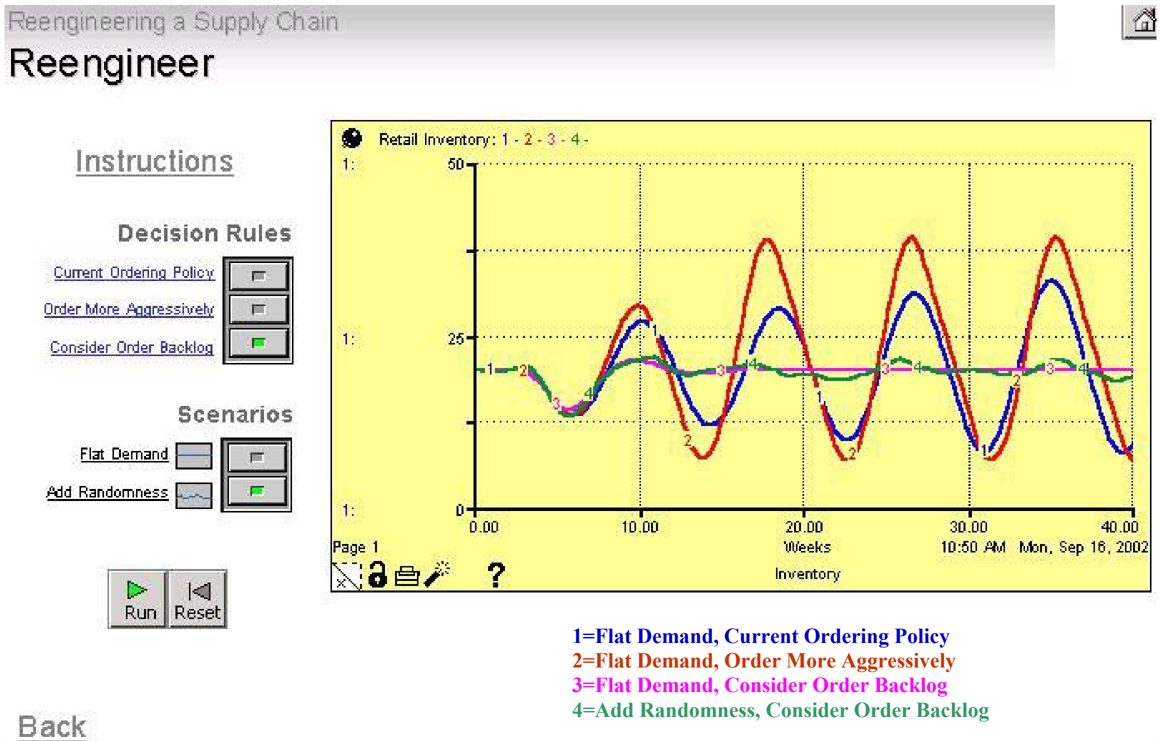

Figure 5: Reengineer

Comparing the four runs in Figure 5, note the following:

1) The “Order More Aggressively” decision rule creates greater inventory fluctuations than the current ordering policy. From the demonstration, “*Ordering more aggressively is a common response to the problem of inventory instability; however, it often exacerbates the problem*.”

2) The “Consider Order Backlog” decision rule, which adds a backlog correction to the current ordering policy, seeks out target inventory quite rapidly, making this the policy of choice in the demonstration.

3) From the demonstration, “*While fluctuation in the demand stream affects inventory levels under the ‘Consider Order Backlog’ policy, the effect is negligible. The ‘Consider Order Backlog’ policy holds up well under a more realistic demand pattern*.”

Read the titles of Figures 1 through 5 repeated here.

Figure 1: Define the problem
Figure 2**Error! Reference source not found.**: Define the As Is
Figure 3: Test the Model

Figure 4: Identify the Cause
Figure 5: Reengineer

The five figure titles are also the five steps that the HPS demonstration follows to discover an ordering policy that will significantly dampen problematic inventory fluctuations.

<u>Feedback Causality in the HPS Example</u>: Having now reviewed the HPS example, the stage is set to use the example as a platform for a discussion of feedback causality. To begin the discussion, see Figure 6. Other than the red highlighting and the notation for the *Target Inventory Loop B1,* Figure 6 is identical to Figure 2 **Error! Reference source not found.**.

As discussed in the HPS example the *order rate to wholesaler* is a function of both the *order delivery rate to customers* and the *target inventory* minus *Retail Inventory*. This ordering rule replenishes the retail inventory delivered to customers and strives to keep *Retail Inventory* aligned with *target retail inventory*. And of course, the retailer knows about the 2-week wholesaler delivery delay, so it is shown in Figure 6.

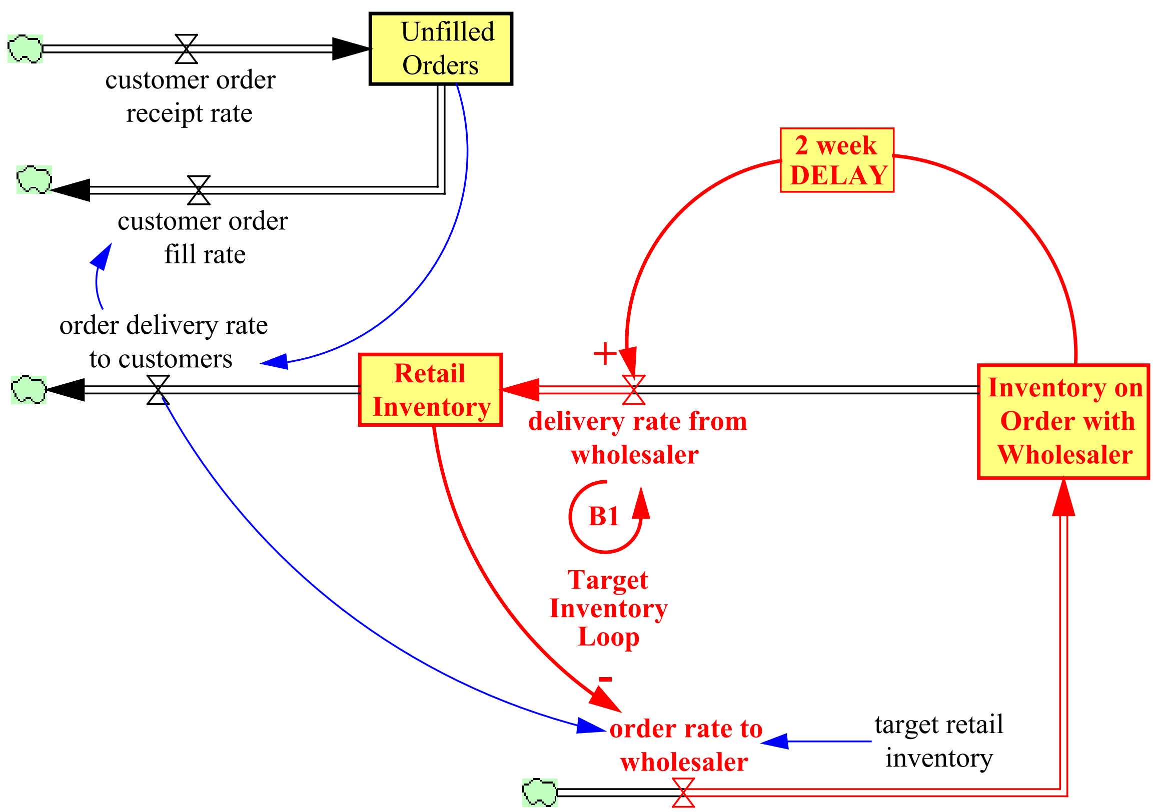

Figure 6: Target Inventory Loop B1

The *Target Inventory Loop B1* in Figure 6 can be described as follows. Assuming all else constant, imagine that *Retail Inventory* is decreased for some reason (say by discovery of an inventory counting error). *Retail Inventory* having decreased, and now being less than *target retail inventory*, the *order rate to wholesaler* increases. (The negative sign on the arrow from *Retail Inventory* to *order rate to wholesaler* signifies that, in response to movements in the former, the latter moves in the opposite direction). The increased *order rate to wholesaler* causes an immediate increase in the *Inventory on Order with Wholesaler*. However, this increase is not reflected in an increased *delivering rate from wholesaler* until two weeks later. (The plus sign on the arrow from *Inventory on Order with Wholesaler* to *delivery rate from wholesaler* signifies that, in response to movements in the former, the latter moves in the same direction, albeit in this case with a two week delay). Finally, finishing our travels around the loop, the increase in *delivery rate from wholesaler* increases *Retail Inventory*. Since the action of the loop is to increase *Retail Inventory* in response to an initial decrease in *Retail Inventory*, the loop is referred to as a balancing loop, hence the "B1" label. (Had the action of the loop been to decrease *Retail Inventory* in response to the initial decrease, the loop would be referred to as a reinforcing loop, with an "R" label.)

The reason for the oscillations in response to a step increase in customer orders (see the oscillations in Figure 3 and Figure 4) is that the ordering policy does not account for another feedback loop that is always present, the *Order Delay Loop B2* (See Figure 7).

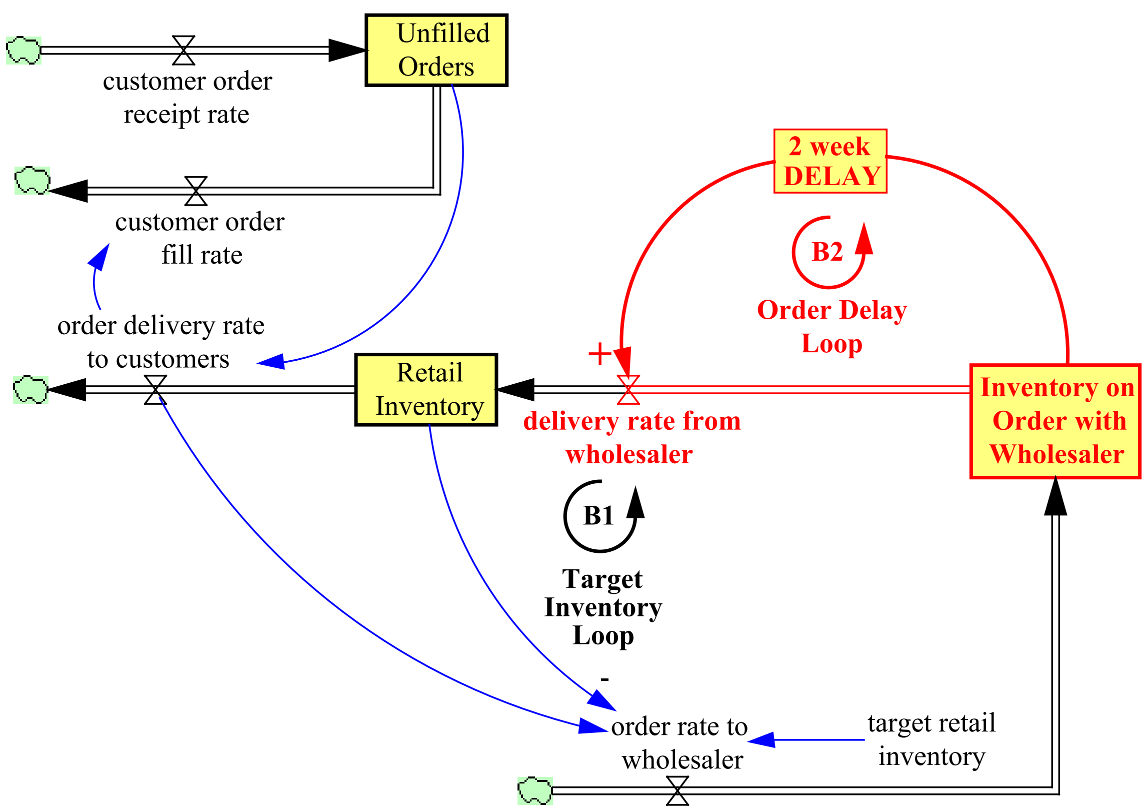

Figure 7: Order delay loop B2

The operation of the *Order Delay Loop B2* loop is as follows. In general, if *Inventory on Order with Wholesaler* increases (say, due to a step increase in *order rate to wholesaler*), then *delivery rate from wholesaler* increases as well, but with a two-week delay. In response to the increase in *delivery rate from wholesaler*, *Inventory on Order from Wholesaler* decreases (relative to what it would have been had *delivery rate from wholesaler* not increased). Since the action of the loop is to decrease *Inventory on Order with Wholesaler* in response to an initial increase, the loop is a balancing loop and so labeled B2.[12]

Why oscillations occur. The model is started with all flow rates equal to one another, and all the stocks therefore constant in a dynamic equilibrium, with *Retail Inventory* equivalent to *target retail inventory*. Suddenly, *customer order receipts* step up and remain at a new higher value. *Order delivery rate to customers* follows, and *Retail Inventory* begins to decline, becoming less than *target retail inventory*. *Order rate to wholesaler* then increases for two reasons – first to accommodate the step increase in *order delivery rate to customers*, and second, to increase *Retail Inventory* back to equivalence with *target retail inventory*. However, since *delivery rate from wholesaler* won't increase for two weeks, *Retail Inventory* remains less than *target retail inventory*, and, in fact, continues to decline since *order delivery rate to customers* remains greater than *delivery rate from wholesaler*. With *Retail Inventory* continuing to decline relative to *target retail inventory*, *order rate to wholesaler* continues to increase. After two weeks, the initial step increase in *order rate to wholesaler* is reflected in a corresponding step increase in *delivery rate from wholesaler*. Subsequent continuous increases in *order rate to wholesaler* are likewise mirrored two weeks later in corresponding increases in *delivery rate from wholesaler*. *Retail inventory* thereby grows to become larger than *target retail inventory*, and *order rate to wholesaler* correspondingly begins to be reduced to bring inventory back down to the target. The oscillations have begun, and depending on how quickly *order rate to wholesaler* adjusts its orders to bring *Retail Inventory* in line with *target retail inventory*, the model's oscillations will either damp out or increase over time. The oscillations occur because, although the ordering rule accounts for loop B1, it does not account for loop B2.

Improve

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[12] To explain in more detail how the delay in loop B2 works, the stage must be set. Imagine that *order rate to wholesaler* has been constant for more than two weeks. This means that at present *delivery rate from wholesaler* is equal to *order rate to wholesaler*, and *Inventory on Order with Wholesaler* is in dynamic equilibrium (constant with equivalent inflow and outflow). With this as the stage, imagine that there is then a step increase in *order rate to wholesaler*. Now we see the delay begin to operate. *Order rate to wholesaler* is now greater than *delivery rate from wholesaler*. Therefore *Inventory on Order with Wholesaler* begins increasing, and continues to increase for two weeks, at which point there is a step increase in *delivery rate from wholesaler* in response to the two week earlier step increase in *order rate to wholesaler*. Since *delivery rate from wholesaler* is now equal to *order rate to wholesaler*, *Inventory on Order with Wholesaler* is once again in dynamic equilibrium (constant with equivalent inflow and outflow), but at a new higher value than its earlier dynamic equilibrium.

Reducing the oscillations. Recall from the Reengineer step of the HPS Example that adding consideration of *Inventory on Order with Wholesaler* to the ordering rule quickly damps the oscillations. The reason this works is that adding such a consideration produces another feedback loop, the *Order Delay Accounting Loop B3* shown in red in Figure 8 below, that offsets the oscillatory effects of the combination of the *Target Inventory* and *Order Delay* loops.

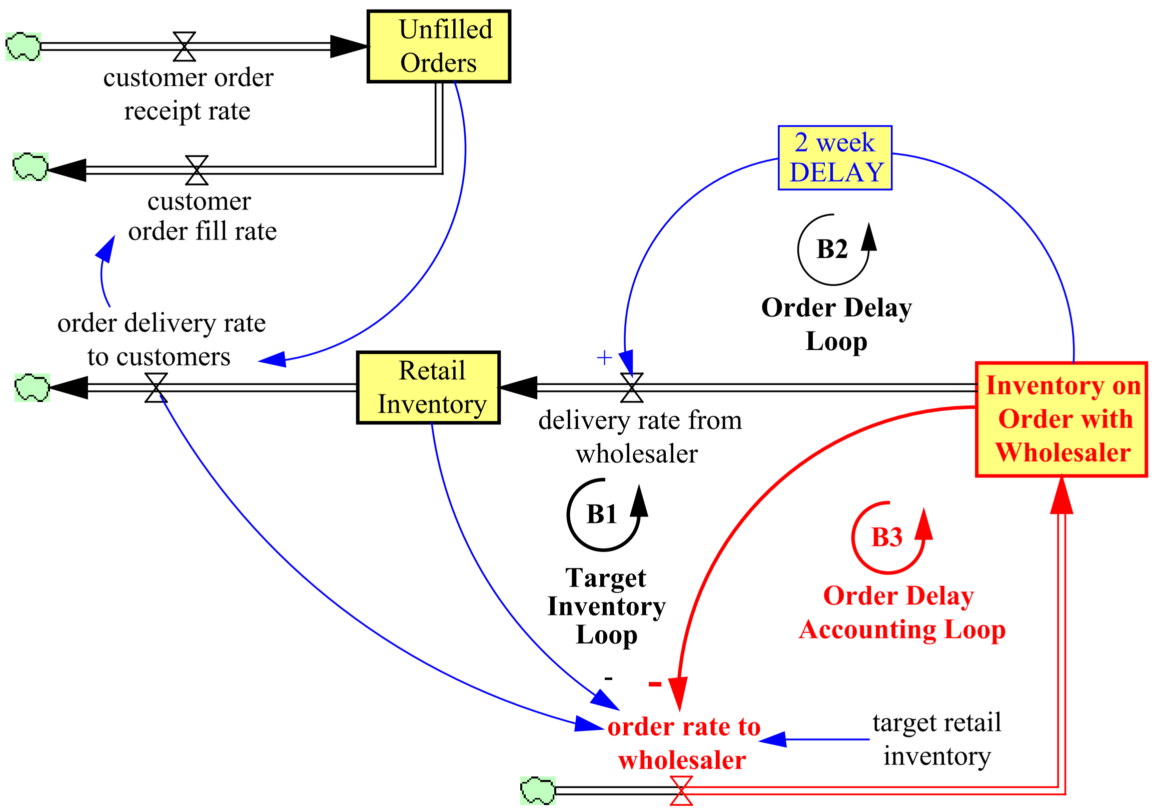

Figure 8: Order Delay Accounting Loop B3

Feedback causality summary: It is the feedback causality (the **interactions** of the *Target Inventory* and *Order Delay* loops) that creates the oscillations shown in Figure 3 and Figure 4. And it is feedback causality (the **interactions** of the *Target Inventory*, *Order Delay*, and *Order Delay Accounting* loops) that produces the much more stable behavior shown in the third and fourth runs in Figure 5. See Chapters 17 and 18 of Sterman (2000) for thorough coverage of this type of stock management system. Hopefully this HPS demonstration has adequately illustrated the role that SD can play as a tactical (DMAIC) Six Sigma tool when business process IPO measures (the Ys) are not (only) a function of a set of Xs, but (also) a function of feedback causality.

Common or Special Cause Variation: Note that feedback causality can produce variations over time that can fall either inside or outside the plus or minus 3 sigma limits defining the boundary between common and special cause variation. Therefore when feedback causality is present, SD can be a useful tool for reducing both common and special cause variation.

Potential Random Variation Effects on Business Process Performance in the presence of Feedback Causality

The HPS example illustrates how SD can improve poor performance created by feedback causality. Once the feedback causes of undesirable performance have been discovered, and solutions identified and implemented, we usually can expect better process/system performance. For example, in the HPS demonstration just discussed, we can expect that implementation of the *Order Delay Accounting Loop B3* in Figure 8 will significantly dampen inventory cost fluctuations. But, there are situations where randomness can intervene and cause process/system performance to deteriorate. Sterman writes:

"*The rain of random noise falling on our systems does play an important role in dynamics… By constantly knocking systems away from their current trajectory* (i.e., the dynamic equilibrium in the HPS example – ed.), *noise can excite modes of behavior that otherwise would lie dormant. … These disturbances can be modeled as random variations around the average behavior given by the equations capturing the feedback structure of the system*."
Sterman (2000, page 128)

Later in his book, Sterman gives an example:

"…*Oliva (1996) developed a model of a bank's retail loan operation to explore the determinants of service quality. Customer demand and worker absenteeism, two important inputs to the model, both exhibited small variations around their averages (the standard deviations were less than 4% of the means). To model these random variations Oliva estimated the autocorrelation functions for each, finding a correlation time constant of about 2 weeks for absenteeism and about 1 week for orders. That is, customer orders this week were weakly dependent on orders last week, but absenteeism tended to persist for longer periods. Oliva also found that the random variations in orders and absenteeism were independent of each other, so each could be modeled as a separate pink noise[13] process. Oliva was then able to simulate the effects of various policies affecting service quality while the model system was perturbed with realistic patterns of orders and absenteeism.*

"Without random noise the loan center remained in equilibrium with demand and capacity in balance and constant service quality. However, when realistic random variations in demand and the workforce were added to the model, quality standards tended to erode over time, even when capacity was sufficient to meet demand on average and even though the random shocks were small. The random variations in demand and

[13] Pink noise is noise modeled "as a process with inertia, or memory – as a process in which the next value is not independent of the last but depends in some fashion on history. Realistic noise processes with persistence are termed 'pink noise'… A simple formulation of pink noise begins with white noise, then smoothes it using some type of information delay." (Sterman, 2000, page 917).

capacity meant the bank occasionally found itself short of capacity. Loan center personnel responded by spending less time with each customer so they could clear the backlog of work each day. These reductions in time per customer gradually became embedded in worker norms. Management interpreted the reduction in time per customer as improvements in productivity caused by their get-tough management policies, unaware that spending less time with customers reduced service quality, eventually feeding back through customer defections to other banks. Oliva found that reducing the time spent per customer caused a significant reduction in the value of loans issued, directly reducing bank revenue. Lower revenues then fed back to financial pressure leading to staff reductions and still more pressure to spend less time on each customer. The resulting positive feedback, if unchecked, could act as a death spiral for the organization. Small, random variations in capacity and orders elicited the latent self-reinforcing quality erosion created by the policies of the bank and the behavior of its workers and managers."
Sterman (2000, pages 921-922)

If performance starts to deteriorate after solutions to the feedback causes of undesirable performance have been implemented (meaning the process is in the DMAIC Control stage), then random noise may induce feedback loop dominance shifts that cause the performance deterioration. In this case, the SD model can be used to test whether this is the case. If model tests indicate that random noise could be causing feedback loop dominance shifts leading to performance deterioration, then the model can be used to test for policies that, in the face of the random disturbances, will reverse the deterioration. Such model testing activities put the process back in the DMAIC Analysis and Improve stages.

Define

Process Maps: Eckes (2001) recommends creating a high-level process map during the Define stage of DMAIC, and then creating sub-process maps during the Analyze stage. These maps typically step through the process and its sub-processes. The stock flow maps in Figure 2, Figure 6, Figure 7, and Figure 8, are another type of map useful in the Design, Analyze, Improve, and Control stages of DMAIC, especially in situations where feedback causality is present.

Measure

Speaking of business processes involving feedback causality, Sterman (2000, p. 854) writes,

"*Modelers must constantly make judgments about whether the time and cost of additional data gathering are justified. In the earliest phase of modeling it is often worthwhile to use experiential data and estimate parameters judgmentally so you can get the initial model running as soon as possible. Sensitivity analysis of the initial model can then identify those parameters and relationships to which the behavior and policy recommendations are sensitive. Parameters that do not significantly affect the results* *need not be estimated with high accuracy, allowing you to focus your limited resources on those factors that do matter so they can be modeled and estimated more accurately.*"

When feedback causality is present, the interaction of the feedback loops typically dominates the influence of most individual parameters on policy and behavior. However, there are usually a few parameters to which model behavior is sensitive. Doing sensitivity analysis on a 'rough' (initial) model can identify these few parameters. The parameters so identified are the ones on which data collection resources should be expended. Thus, when feedback causality is present, SD can focus the data collection effort in the Measure stage of DMAIC.

Tactical (DMAIC) Control

Designing or Improving Processes to Produce Strategic Process Output Time Paths

When feedback causality is present, process owners can use SD models of their processes to monitor and improve them such that they produce the approximate[14] process output and IPO measure time paths expected of the process by the strategic architecture. Traditional Six Sigma tools and processes may be able to be adapted to reduce variation in the process outputs, even if the desired time path of process outputs is not constant.

Dynamic Balanced Scorecards: Eckes' (2001, pages 232-234) recommends the use of balanced scorecards for processes:

"*Each of these scorecards is prepared for either a core process or a series of key subprocesses, depending on what makes sense for a given organization*."

The strategic control section earlier in this paper discussed 'dynamic' balanced scorecards at the firm level. Dynamic balanced scorecards are just as applicable at the individual business process level. The earlier discussion of dynamic balanced scorecards is also applicable at the tactical level. In the same way that firm level strategic architectures can inform the development of dynamic balanced scorecards at the firm level, SD process models (process-level strategic architectures) can inform development of dynamic balanced scorecards at the business process level.

Additional Thoughts on DMAIC and SD

Is SD a Data or Process Tool? Eckes (2001) refers to two approaches to root cause analysis – data analysis and process analysis.[15] In Six Sigma, statistical techniques fall under data analysis. Although data and statistics are involved in parameter estimation,

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[14] 'Approximate' because SD deals with the time path 'tendencies' of systems as described in Meadows (1985), "System dynamicists are not primarily concerned with forecasting specific values of system variables in specific years. They are much more interested in general dynamic tendencies; under what conditions the system as a whole is stable or unstable, oscillating, growing, declining, self-correcting, or in equilibrium."

[15] Eckes (2001) page 113.

historical fit analysis, random variation effects on feedback behavior, and other aspects of SD, SD should probably primarily be classified as a process analysis tool in Six Sigma lingo. In the HPS example, it was process analysis, but supported by historical data, which enabled discovery that the order policy should include consideration of the *Inventory on Order with Wholesaler*.

Stocks and Correlation: Warren (2002, pages 47-50) notes that when stocks are involved in a system, then correlation methods are inappropriate to explain performance. The implications for Six Sigma practice are that there may be process improvement problems for which correlation tools are inappropriate and SD is appropriate.

Other Papers on Six Sigma and SD

Cooper and Canovi (2002) describe the benefits of integrating PA Consulting Group's Rework Cycle Simulation model (a project management model) with the Six Sigma approach "as a new discipline for improving project management."

Vanderminden (2001a) reports on an "investigation of methods of quality improvement for tacit knowledge-based processes in venture capital firms."

Vanderminden (2001b) "explores the reasons for why current Six Sigma methods are inadequate to fully bring quality to the entire organization and how the addition of systems based techniques and tools can help Six Sigma to become a more robust program for organizational excellence."

Appendix 1: The System Dynamics Modeling Process

Sterman (2000) describes the steps of the system dynamics modeling process, excerpted here:

1. **Problem Articulation (Boundary Selection)**

    - **Theme selection:** What is the problem? Why is it a problem?
    - **Key variables:** What are the key variables and concepts we must consider
    - **Time horizon:** How far in the future should we consider? How far back in the past lie the roots of the problem?
    - **Dynamic problem definition (reference modes):** What is the historical behavior of the key concepts and variables? What might their behavior be in the future?

2. **Formulation of Dynamic Hypothesis**

    - **Initial hypothesis generation:** What are the current theories of the problematic behavior?
    - **Endogenous focus:** Formulate a dynamic hypothesis that explains the dynamics as endogenous consequences of the feedback structure.
    - **Mapping:** Develop maps of causal structure based on initial hypotheses, key variables, reference modes, and other available data, using tools such as model boundary diagrams, subsystem diagrams, causal loop diagrams, stock and flow maps, policy structure diagrams, and other facilitation tools.

3. **Formulation of a simulation model**

    - **Specification** of structure, decision rules.
    - **Estimation** of parameters, behavioral relationships, and initial conditions.
    - **Tests** for consistency with the purpose and boundary

4. **Testing**

    - **Comparison to reference modes:** Does the model reproduce the problem behavior adequately for your purpose?
    - **Robustness under extreme conditions:** Does the model behave realistically when stressed by extreme conditions?
    - **Sensitivity:** How does the model behave given uncertainty in parameters, initial conditions, model boundary, and aggregation?
    - **... Many other tests** (see chapter 21)

5. **Policy Design and Evaluation**

    - **Scenario specification:** What environmental conditions might arise?

- **Policy design:** What new decision rules, strategies, and structures might be tried in the real world? How can they be represented in the model?
- **"What if ..."analysis:** What are the effects of the policies?
- **Sensitivity analysis:** How robust are the policy recommendations under different scenarios and given uncertainties?
- **Interactions of policies:** Do the policies interact? Are there synergies or compensatory responses?

Although the above would indicate that the business dynamics modeling process is linear, it is, in fact, iterative as shown in Figure 1.

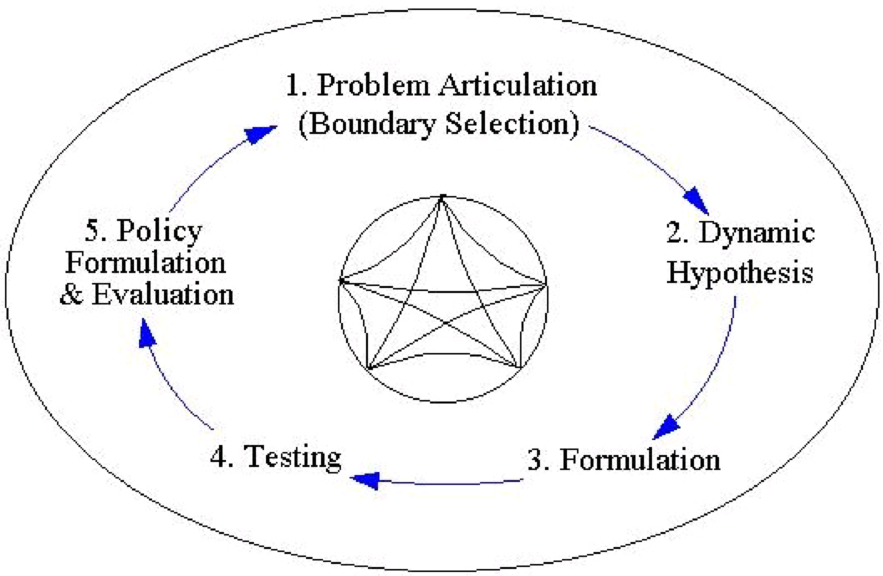

Figure 9 "Results of any step can yield insights that lead to revisions in any earlier step (indicated by the links in the center of the diagram)." [Figure 3-1 from Sterman (2000)]

Other excellent descriptions of the SD modeling process can be found in Richardson (1981) and Saeed (1994). It is very informative to compare these three characterizations of the SD modeling process.

Appendix 2: A Seven Step Strategic Architecture Process

Using SD and the resource-based view of the firm (Barney, 2001, chapter 5; and Grant, 2001, chapter 5), Chapter 6 of Warren (2002) entitled, "The Strategic Architecture – Designing the System to Perform," provides a process for capturing the Strategic Architecture of the firm, excerpted here (combined bold and underlining for emphasis here, and not in original text). After reading Appendix 2, read Appendix 3 for linking business processes to the strategic architecture.

1. Identify the time-path of performance
2. Identify those few **resources** at the heart of the business.
3. Get quantitative – identify the inflows and outflows causing the core **resources** to grow, develop, or decline.
4. Identify how **flows** of each **resource** depend upon existing **levels** of resources and other drivers.
5. Combine the **resource** dependencies from Step 4 into a strategic architecture.
6. Get quantitative – again – to see how the strategic architecture explains performance to date and into the future.
7. Revise policy to uprate performance.

Appendix 3: Business Processes and Strategic Architecture

Following are the "Key Issues" and "Summary" sections of Chapter 9 of Warren (2002). Chapter 9 is entitled, "Building the Capability to Perform." These excerpts are included here to give the reader a sense of how resources, capabilities, and business processes are related, and one way they can work together in the Strategic Architecture of the firm. Review Appendix 2 before reading Appendix 3.

Chapter 9 Key Issues (bold and underlining for emphasis here, and not in original text)

1) **Capabilities** – enabling strategic **resources** to be built and sustained.
2) **Capabilities** combine skills and organizational **processes** for getting things done
3) Learning as **capability** building
4) The impact of **capabilities** on performance
5) Clarifying "core competencies" and the competence of leadership

6) Defining organizational learning – and avoiding organizational forgetting.

Chapter 9 Summary (bold and underlining for emphasis here, and not in original text)

"This chapter has explained how, since performance through time depends on building and sustaining **resources**, **capabilities** must operate through enabling **resources** to be built and sustained (though a few special cases arise where **capabilities** contribute to immediate business performance). **Capabilities** capture how effectively teams in an organization get things done, and come about from the combination of individuals' skills and carefully designed **procedures and processes**. These **processes** are built up over time, and since people carry their skills with them, **capabilities** accumulate and deplete in just the same way as **resources** do.

"Any one **resource** may be dependent on several **capabilities**, so it is important to distinguish these, and follow a careful process to identify the order, scale, cost, and performance outcomes from potential improvements.

"Since the business depends on the entire **resource** system being in good shape, performance is strongly influenced by the strength of all **capabilities** throughout the organization's architecture. Consequently, the quest for what many refer to as a "core competence" (a magic bullet that alone will assure success) is doomed.

"Team learning is measurable as the rate at which any **capability** is building through time – a **process** that arises through feedback from experience at tackling the task of building, developing, or sustaining a **resource**. This learning occurs through accumulating better **procedures**, whether these are codified or merely habits that the team adopts. Learning, when it occurs across all critical **capabilities**, has a powerful impact on the organization's **resource** levels over time, and hence contributes to growing strong, sustainable performance. However, there are powerful mechanisms that drive organizations to forget – many of which have been inadvertently chosen in response to investor pressures.

"'Competence' is a term reserved here for senior management's ability to design a sound strategic architecture of **resources**, **processes**, and policies, to adapt this architecture in the light of emerging problems and opportunities, and to steer performance once the architecture is in place."

Appendix 4: Customer NEEDS and REQUIREMENTS

Eckes (2001) distinguishes between process customers' NEEDS and REQUIREMENTS (applicable to both internal and external customers). On page 51 he writes, "The NEED of a customer is the output or outputs of a process that establishes the relationship between the supplier and customer. REQUIREMENTS are the characteristics that determine whether the customer is happy with the outputs provided."

Here is a simple example. Bolts are the NEED of the customer of a process that manufactures bolts. The customer's REQUIREMENTS are that the bolts have a certain overall length, diameter, thread length, delivery time, etc.

The Six Sigma process is mostly about improving processes, not to better meet customer NEEDS, but rather to better meet customer REQUIREMENTS.[16] SD can sometimes be useful for improving processes to better meet customer REQUIREMENTS, and therefore has a place in the Six Sigma process improvement toolkit. SD can always be useful for improving or designing processes to meet customer NEEDS as they change over time.

Appendix 5: Pande's (2000) Two-Tiered Six Sigma Process

Compare to the first column of Table 1

Tier 1, "The Six Sigma Roadmap" from Pande et. al., (2000) p69
Step 1: Identify core processes & key customers
Step 2: Define customer requirements
Step 3: Measure current performance
Step 4: Prioritize, Analyze & Implement Improvements
Tier 2, "DMAIC" p39 & p69
4a) *Define*: Identify the problem, define requirements, and set goal
4b) *Measure*: Validate problem/process, refine problem/goal, and measure key steps/inputs
4c) *Analyze*: Develop causal hypotheses, identify "vital few" root causes, and validate hypothesis
4d) *Improve*: Develop ideas to remove root causes, test solutions, and standardize solution/measure results
4e) *Control*: Establish standard measures to maintain performance and correct problems as needed
Step 5: Expand & Integrate the Six Sigma System

[16] Eckes, 2001, pages 51, 60-64, and 71.

References:

Six Sigma and SPC (Statistical Process Control) References

Breyfogle III, Forrest W., James M. Cupello, and Becki Meadows (2001) Managing Six Sigma: A Practical Guide to Understanding, Assessing, and Implementing the Strategy that Yields Bottom-Line Success. Wiley Interscience.

Brue, Greg (2002) Six Sigma for Managers. McGraw-Hill.

Chowdhury, Subir (2001) The Power of Six Sigma. Dearborn Trade

Eckes, George (2001) The Six Sigma Revolution: How General Electric and Others Turned Process Into Profits. Wiley

Harry, Mikel and Richard Schroeder (2000) Six Sigma: The Breakthrough Management Strategy Revolutionizing The World's Top Corporations.. Doubleday

George, Michael L. (2002) Lean Six Sigma: Combining Six Sigma Quality with Lean Speed. McGraw-Hill

Pande, Peter S., Robert P. Newuman, and Roland R. Cavanagh, (2000) The Six Sigma Way: How GE, Mortorola, and Other Top Companies are Honing Their Performance. McGraw-Hill.

Pande, Peter S., Robert P. Newuman, and Roland R. Cavanagh, (2002) The Six Sigma Way Team Fieldbook. McGraw-Hill

Wheeler, Donald J. and David S. Chambers (1992) Understanding Statistical Process Control (2nd Edition). Knoxville, TN: SPC Press, Inc.

Wheeler, Donald J. (1993) Understanding Variation: The Key to Managing Chaos. Knoxville, TN: SPC Press, Inc.

System Dynamics and Strategy Dynamics References

High Performance Systems, Inc. (2001) Reengineering a Supply Chain Demonstration. Hanover, N.H. USA. File named “Supply chain reengineering.ITM” which downloads with the ithink V7 Demo from http://www.hps-inc.com.

Meadows, D.H., and J. Robinson (1985) *The Electronic Oracle: Computer Models and Social Decisions.* Chichester, England: John Wiley and Sons.

Oliva, R. (1996) A Dynamic Theory of Service Delivery: Implications for Managing Service Quality. PhD thesis. MIT Sloan School of Management, Cambridge, MA 02142 (unpublished)

Richardson, George P. & Alexander L. Pugh III (1981) *Introduction to System Dynamcis Modeling* Portland, Oregon. Productivity Press.

Saeed, Khalid (1994) *Development Planning and Policy Design.* Avebury, Hants, England

Sterman, John D. (2000) Business Dynamics: Systems Thinking and Modeling for a Complex World. McGraw-Hill. See http://web.mit.edu/jsterman/www/BusDyn2.html

References dealing with both Six Sigma and System Dynamics

Cooper, Kenneth G. and Adolfo Canovi (2002) Return of the Learner: Six Sigma Meets the Rework Cycle. Paper presented at the Fifth European Project Management Conference, PMI Europe 2002, Organized by the PMI France Sud.

Vanderminden, Peter A. (2001a) Quality Improvement in Knowledge Based Organizations: Capturing Tacit Knowledge to Aid Organizational Learning in Venture Capital Decisions. Paper presented at the 19th International Conference of the System Dynamics Society in Atlanta, GA, 2001.

Vanderminden, Peter A. (2001b) Combining Six Sigma and Systems Methods for Quality Improvement of Intangible Value Creation Processes. Unpublished paper.

Business Strategy References

Barney, J.B. (2001) Gaining and Sustaining Competitive Advantage (2nd edition) Reading, MA: Addison-Wesley

Grant, R.M. (2001) Contemporary Strategy Analysis (4th edition) Cambridge, MA: Blackwell.

Warren, Kim (2002) Competitive Strategy Dynamics. Wiley

General Balanced Scorecare References

Kaplan, R., Norton, D., (1992). “The Balanced Scorecard - Measures That Drive Performance.” Harvard Business Review 70(1): 71-79.

Kaplan, R., Norton, D., (1993). “Putting the Balanced Scorecard to Work.” Harvard Business Review 71(5): 134-142.

Kaplan, R., Norton, D., (1996a). The Balanced Scorecard: Translating Strategy into Action. Boston, Massachusetts, Harvard Business School Press

Kaplan, R., Norton, D., (1996b). “Linking the Balanced Scorecard to Strategy.” California Management Review 39(1): 53-79.

Dynamic Balanced Scorecard References

Akkermans, Hank and Kim van Oorschot (2002) Developing a Balanced Scorecard with System Dynamics. Proceedings of the Twentieth International Conference of the System Dynamics Society held in Palermo, Italy. System Dynamics Society, Rockefeller College of Public Affairs and Policy at the State University of New York, Albany, NY.

Bititci, U., Turner, T., (2000). “Dynamics of Performance Measurement Systems.” International Journal of Operations & Production Management 20(6).

Corrigan, J., (1998). "Performance Measurement: Knowing the Dynamics." Australian Accounting 68(9): 30-31.

Davis, A., O'Donnell, J., (1997). "Modeling Complex Problems: System Dynamics and Performance Measurement." Management Accounting-London, 75(5): 18-30.

Diehl, E., Sterman, J. D., (1995). "Effects of Feedback Complexity on Dynamic Decision Making." Organizational Behavior & Human Decision Processes. 62(2): 198-215.

High Performance Systems, Inc. (2001) Dynamic Balanced Scorecard Demonstration, Hanover, N.H. USA. Files named "Dynamic Balanced Scorecard.itm" and "Simple Balanced Scorecard.itm" which download with the ithink V7 Demo from http://www.hps-inc.com.

High Performance Systems, Inc. (2000?) Balancing the Corporate Scorecard 2.0. Hanover, N.H. (This is a "Practice Field Interactive Simulation" on CD produced for Harvard Business School by High Performance Systems, Inc.).

Kim, D. H. (1997). "From Key Success Factors to Key Success Loops." The Systems Thinker 8(5): 6-7.

Kreutzer, W. B. (1991a). "A Systems Thinking Approach to Executive Information Systems." The Systems Thinker 3(7): 8-9.

Kreutzer, W. B. (1991b). "S**4: Strategy Support Simulation System." The Systems Thinker 2(10): 8-9.

Norton, David P. (2000) "*Is Management Finally Ready for the 'Systems Approach'?"* Balanced Scorecard Report. Harvard Business School Publishing. Vol. 2, No. 5, September-October 2000

Richmond, B., (1999). Using the Balanced Scorecard to Leverage Penetration of Systems Thinking. Hanover, N.H., High Performance Systems.

Richmond, Barry (2001). "*A New Language for Leveraging Scorecard-Driven Learning*." Balanced Scorecard Report, Harvard Business School Publishing, Vol. 3, No. 1, January-February 2001.

Sloper, P., Linard, K., Paterson, D.,. (1999). "Towards a Dynamic Feedback Framework for Public Sector Performance Management." 1999 International System Dynamics Conference - Wellington New Zealand.

Stevenson, R., Wolstenholme, E., (1999). Value Chain Dynamics - Applying System Dynamics to Support Value Thinking. 17th International Conference of the System Dynamics Society and 5th Australian & New Zealand Systems Conference, Wellington, New Zealand.

Todd, David (2000) A 'Dynamic' Balanced Scorecard: The Design and Implementation of a Performance Measurement System in Local Government. Unpublished Master's Thesis. School of Management Science and Information Systems, University of Auckland, New Zealand.

Warren, Kim (2002) Competitive Strategy Dynamics. Wiley (pages 276-279)