# The Value of System Dynamics in the Wider World: an Outside-In View

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## Abstract

System Dynamics is no longer new, but its impact on the wider world is still quite immature. Newer technologies have been taken up much faster and more broadly, bringing about huge societal changes. Is System Dynamics fundamentally different, and do essential characteristics necessarily restrict it to narrower impacts and a slower rate of diffusion? The answers lie in innovation. This paper describes how innovation by practitioners will profoundly change the practice of System Dynamics and its societal impact.

## Introduction

This 50th year since the discovery of System Dynamics is an appropriate time to reflect on what we have accomplished and what lies before us. These particular reflections are based on my 25 years doing management consulting based entirely on System Dynamics.

Thirty years ago, as an undergraduate, I attended a lecture Jay Forrester gave on System Dynamics. I don't remember what made me attend or anything specific that Professor Forrester said, but it was revelatory and it changed my life. It was almost religious in its transforming impact. I have devoted all but three of the intervening years to the commercial consulting-based practice of System Dynamics.

Of course that does not make me unique. The System Dynamics Society is filled with people whose lives were changed by Jay Forrester's realization that the world is driven by feedback loops which can be reproduced in computerized form and thereby understood and managed. We have seen the tremendous power of that discovery demonstrated again and again, in almost every aspect of human life. To me it is one of the greatest scientific revelations of the past century, and I count myself hugely fortunate to have been drawn in while it was relatively new.

Although System Dynamics can no longer be called new, its impact on the wider world is still quite immature. Other new technologies have been taken up much faster and more broadly, bringing about huge societal changes. I am not alone in having found this both puzzling and frustrating. Why should System Dynamics be different? Do essential characteristics necessarily restrict it to narrower impacts and a slower rate of diffusion, or are there other explanations? Is it in our power to change these things, and if it is, what can System Dynamics become to the wider world in this still-young century?

I believe that the answers to these questions lie in the concept and process of innovation. It is well established that innovation is very different from invention. Invention creates new things, tools, methods, technologies, processes, concepts. Innovation creates new markets by satisfying felt needs of customers. A felt need may long predate the innovation that sparks rapid growth, or it can be as new as the innovation itself and even sparked by it. An invention will often linger unnoticed for years until some innovator employs it in a form that meets a felt need, whereupon its use and impact grow rapidly. Innovations often combine multiple inventions in synergistically valuable combinations that trigger growth.

As an example consider the Douglas DC-3, the first commercially successful airliner. The DC-3 triggered explosive growth of the air transport market because it was the first aircraft to integrate five technical inventions that proved highly synergistic:

- Monocoque construction (eliminating high-drag braces, struts and wires)
- The radial air-cooled engine (offering increased power-to-weight ratio and enabling greater speed)
- Retractable landing gear (eliminating a major source of high-speed drag)
- Adjustable-pitch prop (reconfigurable for high thrust at both high and low speeds)
- Flaps (reconfiguring the wing for high lift at low landing and takeoff speeds)

Note that each of these inventions was technically proven at least a decade before the DC-3 was introduced. Yet none of them was in widespread use and none had triggered market growth. The problem was that not one of these successful inventions would pay for itself when implemented on a stand-alone basis. But there existed powerful technical synergies between the five inventions, and unleashing those synergies was the key to the DC-3's success. The power of that synergy and the crucial contribution of each individual invention to it are dramatically illustrated by a market failure of The Boeing Company. Several years before Douglas introduced the DC-3, Boeing brought out a new aircraft for the same market. It integrated all but one of the five inventions embodied in the DC-3 – it was missing only the flaps. That lack made it a technical and market failure, selling in tiny numbers compared to the DC-3. This illustrates a fundamental characteristic of knowledge-based innovations: the innovation and resulting market growth cannot happen until <u>all</u> of the synergistic inventions have been integrated. As we will see, this characteristic has a great deal to teach us about growth of demand for System Dynamics.

System Dynamics is an invention, as was the DYNAMO simulation language. Calibration and validation of System Dynamics models is a related invention that came along a little later. The personal computer is yet another invention, one that greatly increased the accessibility and reliability of System Dynamics. Together these inventions transformed the lives of many Society members. If there were ten million of us today we might call that combination a major innovation. That there aren't even ten thousand of us suggests that it constitutes a small innovation, one that does not yet meet broadly felt needs in the wider world. But that doesn't mean that such needs do not exist or that System Dynamics cannot meet them. This paper describes how innovation by practitioners is changing the practice of System Dynamics and will profoundly change its societal impact.

## The Wider World and its Unfelt Needs

The wider world clearly has not felt a strong need for System Dynamics. If it did there would be much broader and faster-growing demand for such models and modelers. The absence of a strong felt need has been puzzling and sometimes frustrating, since System Dynamics has so thoroughly demonstrated its power in so many settings. Can the need for System Dynamics really be so narrow and episodic as its applications? Or is there a broad unfelt need, and if so, why is it unfelt? Does the wider world simply fail to realize that System Dynamics can meet important needs? Or are the wider world's needs unrecognized because they are somewhat different from what System Dynamics practitioners think they are, or should be?

Answering these questions requires that we observe and make generalizations about the situation in the wider world. Such generalizations are easy to criticize, but understanding what is generally true about a potential market is critical for successful innovation. So what do System Dynamicists need to know about the wider world that could and should be making much greater use of System Dynamics?

Let's begin diagnosis with the following observation: the wider world generally does not understand that things are driven by feedback loops, and that reproducing these dynamics in the computer makes them visible, understandable and manageable. The prevalence of this limited view is amply demonstrated by the wide range of traditional (that is, non-dynamic) analysis tools, most of which cut off all feedback loops and substitute numerical inputs for the missing loops. In a feedback-driven world, cutting off feedback loops in analytical tools has profound effects on the breadth, speed, practicality and reliability of tools and analyses, effects that go mostly unrecognized in the wider world.

First, even in its more modest corners the wider world runs on a great many feedback loops. Cutting off that multiplicity of feedback loops necessitates a lot of substitute numerical inputs, which is one reason why many traditional analysis tools are so input-intensive. Being inherently input-intensive tends to make traditional tools rather labor-intensive and slow to turn around. As a practical matter it also limits representational breadth, because greater breadth requires a wider range of input types and sources that becomes much more difficult to obtain and manage. That is one reason why traditional analysis tools usually stay within the traditional functional boundaries of an organization.

In a feedback-driven world, cutting off feedback loops creates an immediate tool-reliability problem. Most traditional tools aim at behaving *like* some aspect of the real world without actually reproducing the real-world structure that produces the behavior. Try to mirror non-linear dynamic behavior without the benefit of feedback loops, and the reliability deck is stacked against you right from the start. Being inherently input-intensive compounds this tool-reliability problem, because it is practically impossible to maintain internal consistency among a large number of inputs except in the very short term. To do so would require an ability to intuit how numerous non-linear feedback loops interact over time, and the human mind doesn't work that way. So substantial input inconsistencies are unavoidable with traditional analysis tools, and those tools generally cannot say where or how much those inconsistencies hurt reliability.

The reliability problem doesn't end there. Cutting off feedback loops artificially increases the number of degrees of freedom of the traditional analysis tool to well in excess of both its real-world counterpart and the amount of corroborative real-world historical data. Such a tool is said to be underdetermined, and underdetermined tools cannot be meaningfully calibrated or validated using real-world data as an independent benchmark. The inability to take advantage of the information normally gained from such processes further increases unreliability of traditional tools and analyses.

These reliability problems tend to push the builders of traditional tools to ever-greater levels of representational detail. Simple, high-level traditional tools may be usefully illustrative but they can't deliver quantitative reliability, and most people believe that's because they don't represent the real world in sufficient detail. Their quest for reliability from the inherently unreliable encourages expansion of bottom-up detail that makes traditional tools more and more input-and labor-intensive. And increased representational detail makes comprehensiveness more difficult to achieve.

To summarize the situation, the wider world relies on traditional analysis tools that:

- Are inherently input- and labor-intensive, hence slow;
- Embody fragmentary, bottom-up, non-dynamic representations;
- Employ a wide range of inconsistent data and analysis methods, and usually don't communicate or connect well with each other; and
- Have substantial built-in reliability problems.

As a rule, decision-makers cannot look to these traditional tools for broad, integrative or comprehensive analyses. They must attempt to mentally integrate the disparate and often inconsistent outputs from all these tools to arrive at some semblance of a comprehensive view. In the face of more than three or four connected real-world feedback loops, the completeness and reliability of the resulting picture will necessarily be suspect.

Clearly the wider world needs and would benefit from something better, and just as clearly System Dynamics can meet that need. But that need is not felt in the wider world because expectations have been and are being shaped almost entirely by the inherent limitations of traditional tools. Most of the wider world does not know that there is any alternative. And the minority who are aware of System Dynamics as an alternative have too little experience with it to recognize the full shape and size of the need it might meet.

System Dynamics practitioners attempt to make this a felt need mostly through short- or long-term education. Consultants educate in the short term. They say "The underlying reality of your problem is dynamic, so wouldn't it be great to actually simulate those dynamics?" Educators tend to educate in the long term – they show the decision-makers of one or two or three decades from now that the world is dynamic and that simulating dynamics helps. Gurus focus on educating today's decision-makers in the very short-term. Abundant experience suggests that System Dynamics practitioners educate pretty well on all fronts, but it also demonstrates the inherent limitations of this approach – short-term education is narrow and situation-specific and long-term education takes a very long time to show results. Neither has come even remotely close to creating a broad felt need for System Dynamics.

The hard truth is the wider world does not want System Dynamics models, indeed, it does not want models of any kind. The wider world often wants the understanding and control that it hopes can be gained from models, but only if there is no simpler, faster, cheaper way to get understanding and control. There are more and more traditional models and modelers competing for share of mind-space all the time, so the System Dynamics mind-share based on education is almost certainly in long-term decline. In other words, the purveyors of traditional tools and their limitations are strengthening the wider world's acceptance of those limitations far faster than we can educate them about the alternative. We are like the firm that prides itself on 12% annual growth when its market is shooting ahead at a 25% rate. It is difficult to see how our tiny community can ever educate enough people to create a broadly felt need for System Dynamics or Systems Thinking or anything related to them. That doesn't say that we should abandon our education efforts, but neither should we expect a result they cannot deliver.

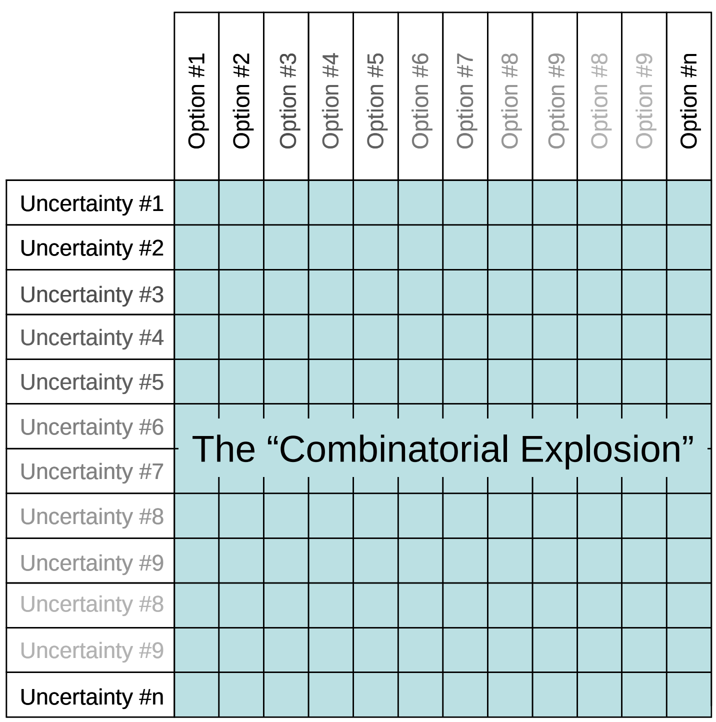
This bleak picture is far from conclusive because educating is not the same as innovating. Innovating creates markets, and we have barely begun to explore the innovative possibilities of

System Dynamics. Turning those possibilities into realities requires moving beyond unfelt needs to understand and cater to the needs that the wider world already feels.

### Felt Needs in the Wider World

Let's start at a high level with one of the central incongruities of modern times. Markets, economies and organizations are all comprised of many different elements, and everyone agrees that those elements are highly interconnected. Yet nearly all of our analysis tools, management methods and even our organizational structures treat those elements as if they were separated or separable. They ignore almost entirely the connections between elements. This ignorance results in systemic sub-optimization that causes big value loss in nearly all types of organizations. Most decision-makers will quickly agree that the connections between elements are important, that they have no good way of managing or even seeing how those connections operate, and that the ability to do so would help solve big problems and add significantly to organizational value. Clearly this is a strongly felt and almost universal need, a need that System Dynamics is uniquely well equipped to satisfy. But we have not yet innovated to meet it, so we have not seen the explosive market growth that results from such innovation.

Let's get more specific with a reality that decision-makers in the wider world see all too clearly: a "combinatorial explosion" of uncertainties and decision options. Being a consultant I'll portray this combinatorial explosion using the ever-popular two-dimensional matrix. On one axis we'll array the multiple dimensions of uncertainty faced by a hypothetical decision-maker. The ideal decision-maker will know (through analysis) how each dimension of uncertainty affects the health and performance of the entity that concerns him. Since those uncertainties are not mutually exclusive, the ideal decision-maker will also know (through analysis again) how all the relevant uncertainty combinations affect that entity.



On the other axis we'll lay out the decision options open to our ideal decision-maker. He or she will of course know (through analysis) how each option affects the entity of concern. And this ideal will also know how all relevant option combinations affect that entity.

Many decision-makers are experiencing increasing numbers of both uncertainties and options. It doesn't take very many options and uncertainties for the combinatorial explosion to become real. And the explosion is actually bigger and faster than first appears, because our ideal decision-maker will want to know how every relevant option combination will affect the entity in the face of every relevant uncertainty combination. That transforms the combinatorial explosion like a move from conventional to tactical nuclear weapons.

Now compare that exploded range of analyses with the capacity of traditional tools. The real-world reality is that traditional tools are far too slow and labor-intensive to analyze more than a tiny fraction of all the relevant uncertainty/option combinations. Decision-makers don't have the time, the data or the labor to run more than a few rifle-shot analyses, and the rest of the performance envelope goes unmapped – it is literally *terra incognita*. Decisions are based on a few pin-pricks of not-very-reliable light in a sea of blackness. This harsh reality underlies much of the risk attendant on decision-making, actually increasing risk in two ways:

- The vast preponderance of blackness encourages and even forces cautious decisions that fall well short of optimal performance for the entity in question. This is the recipe for systemic sub-optimization, with big consequences – in industry after industry we find that even the best-run firms fall at least 30% short of the performance they could achieve with available assets;
- Decisions may not be robust in the face of unanalyzed uncertainties that turn into reality, and this is the recipe for big, unanticipated downside problems.

The wider world is so accustomed to this reality, dictated as it is by the limitations of traditional tools, that decision-makers usually give little thought to changing either the tools or the reality. But that doesn't mean they aren't aware of the combinatorial explosion and worried by its unquantified but strongly suspected impact on the quality of analysis and decision-making. The moment decision-makers begin to see a possibility of changing the reality, their worry typically bursts forth as a strongly felt need to reduce the deleterious effect of the combinatorial explosion on decision-making. The problem of the combinatorial explosion is prevalent and recognized by decision-makers in most industries and markets, so this is a broadly felt need. As I will show this is another need that System Dynamics is uniquely suited to meet, given innovation.

Notice that this felt need revolves around "the decision-makers' stuff" – <u>their</u> decisions and the context in which they make them. The felt need does not revolve around "the modelers' stuff" – feedback loops, model speed, etc. Markets don't care about technical tool characteristics in absolute terms. Markets respond to what those tools can do for them in their own setting, to the value they can create based on tool use. On that basis we can consider how well System Dynamics matches up to the felt need resulting from the combinatorial explosion.

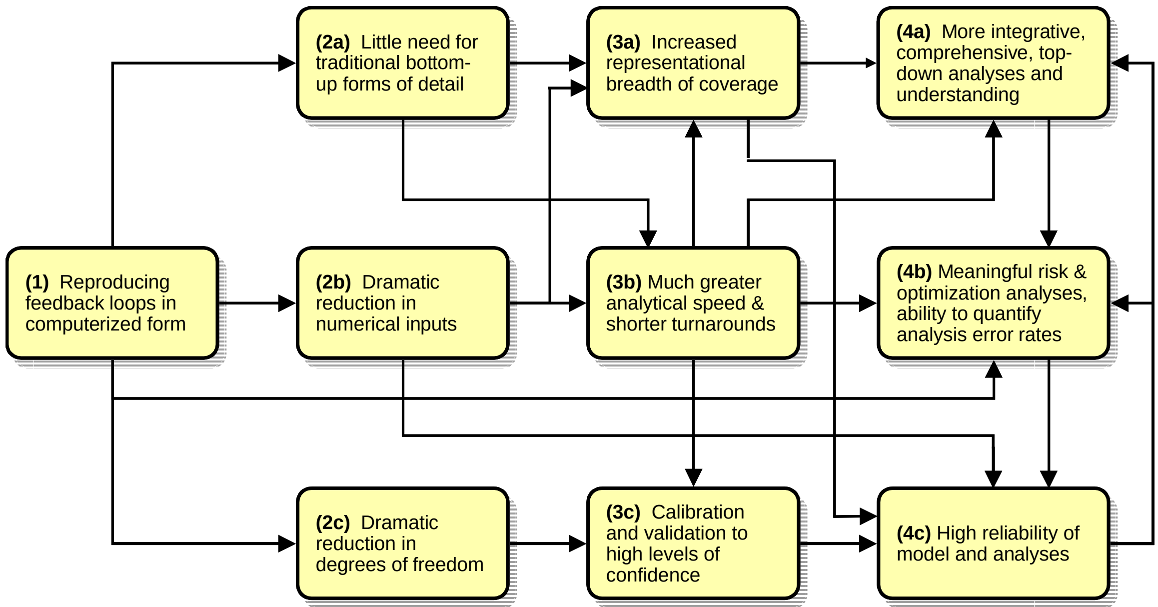
**System Dynamics and the Felt Need from Combinatorial Explosion**

In evaluating the fit between System Dynamics and the felt need that results from the decision-makers' combinatorial explosion, we need to answer two questions:

1) Is there a good match between System Dynamics capabilities and the felt need?

2) Is System Dynamics uniquely able to satisfy the felt need?

The diagram below shows the elements of this evaluation and the connections between them.




The foundation is item (1), reproducing feedback loops in computerized form. This is unique to System Dynamics, and when done effectively the dynamic model differs significantly from traditional tools in three important ways.

(2a) There is little need for traditional bottom-up forms of detail. System Dynamics models get their reliability from feedback detail rather than bottom-up structural detail.

(2b) There is a dramatic reduction in numerical inputs. System Dynamics models compute internally most of what would be numerical inputs in a traditional analysis tool.

(2c) There is a dramatic reduction in the degrees of freedom. In connecting the various factors in the System Dynamics model, feedback loops restrict the degrees of freedom to match those in the real world. Traditional tools artificially inflate the degrees of freedom by cutting off those feedback loops.

These are technical differences that markets will not care about or pay much attention to. But they result in significant representational and operational differences for the System Dynamics model and analyses performed with it.

(3b) Reduced bottom-up detail (2a) and numerical inputs (2b) allow much greater analytical speed and shorter analysis turnaround times.

(3a) Higher speed and shorter turnarounds (3b) combined with reduced bottom-up detail (2a) and numerical inputs (2b) to allow much greater representational breadth of coverage. This enables the System Dynamics modeler to draw much wider model boundaries than would be reliably feasible with traditional tools.

(3c) Reduced degrees of freedom (2c) and the rapid iteration made possible by higher speed and shorter turnarounds (3b) allow calibration and validation of System Dynamics models to high levels of statistical confidence, something quite impossible with most traditional tools.

Markets will not generally perceive or appreciate these representational and operational differences, but they contribute to fundamental differences in analytical capability that directly address the felt need arising from the combinatorial explosion.

(4c) Calibration and validation (3c) directly support much higher model and analysis reliability, and make reliability measurable and demonstrable (often impossible with traditional tools). Increased representational breadth (3a) directly supports model and analysis reliability by encompassing more of the performance-driving dynamic interdependencies that most traditional tools ignore.

(4a) Increased representational breadth (3a) delivers analyses that are more comprehensive and integrative than would be possible with traditional tools. Greater analytical speed and shorter turnarounds (3b) make possible the increased number of simulations needed to support more integrative and comprehensive analyses. Increased model and analysis reliability (4c) provide the credibility foundation needed to have confidence in more integrative and comprehensive analyses.

(4b) Reproducing feedback loops (1) directly supports more meaningful risk analyses in the form of dynamic Monte Carlo simulations. Monte Carlo techniques often yield unrealistically broad outcome distributions when employed with traditional analysis tools, because those tools are missing the feedback loops that constrain real-world outcomes. Dynamic Monte Carlo analyses are synergistic – the value of Monte Carlo techniques is enhanced by reproducing feedback loops, and vice versa. Dynamic Monte Carlo analyses are also the means for quantifying analysis error rates. High analytical speed (3b) is critical for: a) analysis of multiple uncertainty combinations; b) optimizing across decision options in the face of multiple uncertainties; and c) quantifying analysis error rates. More integrative and comprehensive analyses (4a) are essential to have confidence in the robustness of risk and option-optimization outcomes.

Notice that there is a self-reinforcing technical feedback loop connecting items (4a), (4b) and (4c). These mutually supportive analytical characteristics are the keys to solving the decision-maker's combinatorial explosion problem. The speed of a properly developed System Dynamics model allows comprehensive mapping of performance for the entity of concern across all identified uncertainties and decision options. We all know the compounding power of positive feedback loops, and it certainly applies here. Instead of peeking at the future through the keyholes of their traditional rifle-shot analyses, System Dynamics gives decision-makers the keys to their doors and enables them to walk around together, not just in the future, but in multiple possible futures. The high reliability of the System Dynamics model and analyses make such excursions much more valuable than they could ever be with traditional tools alone. In the hands of capable decision-makers, the ability to see and understand and manage the future is worth a great deal. System Dynamics can solve the combinatorial explosion problem and the solution is unique – we have found no combination of traditional tools that can deliver it.

I have left off one other powerful positive feedback loop from this diagram – using System Dynamics to help decision-makers deal with the combinatorial explosion tends to generate more opportunities to reproduce feedback loops in computerized form!

But a cautionary note is in order here. One cannot conclude that use of the System Dynamics invention alone will solve the combinatorial explosion problem. Two examples demonstrate this.

- When calibration and validation of System Dynamics models was a new invention, some practitioners opposed it on the grounds that there was too much randomness in the real-world system to make it feasible, safe or desirable. They maintained that only general replication of the real-world behavior mode was possible or desirable. Today we know that effective calibration and validation yield significantly more reliable data, simulators and analyses, and what is more important, make that reliability measurable and demonstrable. Without the invention of calibration and validation (3c) System Dynamics cannot solve the combinatorial explosion problem. No innovation, no satisfying of the felt need, and no market growth.
- Two different consulting firms developed System Dynamics models of regional electric power markets. One of these simulators followed best System Dynamics practice, was carefully calibrated and validated and used with great success. It took about ten seconds to simulate 40 years of past and future market behavior with high fidelity. The other simulator included all of the bottom-up details of traditional, non-dynamic power-market models and it needed twelve hours to simulate less than 20 years of market behavior. Failing to capitalize on reduced need for traditional bottom-up details (2a) made it run almost 10,000 times slower (3b) which rendered it impossible to calibrate or validate (3c). No one knew to what extent they could rely on analysis results, so they were literally and necessarily unreliable (4c). Although the model content was theoretically more comprehensive, its lack of speed made it impossible to conduct meaningful risk and optimization analyses (4b), or the iterative simulations needed for genuinely comprehensive analyses (4a). Such models cannot solve a decision-maker's combinatorial explosion problem. Again, no innovation, no satisfying of the felt need, and no market growth.

It is worth noting that calibration and validation represent one invention (the scientific method) applied to the practice of the System Dynamics invention. The System Dynamics model is the explicitly stated hypothesis required by the scientific method, and model calibration against a historical benchmark constitutes the requisite iterative process of falsification testing followed by refinement of the hypothesis and yet more falsification testing. When the model-as-hypothesis can no longer be falsified using available information, we do not conclude that it is either correct or true, but we have established that it is the best hypothesis available given available information. Consistent with the definition in Webster's Unabridged Dictionary, validating System Dynamics models means demonstrating that they are, *"…well grounded in principles or evidence… able to withstand criticism or objection…effective…robust."*

Integrating the System Dynamics invention and the calibration/validation invention is a good example of a limited innovation and its market consequences. This innovation spurred the growth of management consulting based on System Dynamics. There was no market for such consulting before calibration and validation became part of System Dynamics practice, and it is difficult to imagine that consulting based on System Dynamics could have grown as it has without them.

But management consulting based on System Dynamics has not been sufficiently innovative to sustain many of the consultancies that entered that market, nor has it resulted in a broadly felt need for System Dynamics or Systems Thinking or their benefits. Further innovation is obviously needed for that to occur, beginning with the focused application of System Dynamics to broadly felt needs as exemplified by the combinatorial explosion problem. But that is only the first dimension of needed innovation, and one which will itself force innovation on other dimensions. The final section of this paper focuses on complementary dimensions of System Dynamics innovation already underway.

**Additional Dimensions of System Dynamics Innovation**

It is important to note that not all innovations are technological. I believe that future System Dynamics innovations will be mostly non-technical in nature. This is demonstrated by the fact that we have at our disposal today the full technical means to solve the combinatorial explosion problem for decision-makers in many different walks of life, yet we are not yet seeing the market growth that must accompany the satisfaction of such a broadly felt need. It is primarily non-technical dimensions of innovation that are missing, and successful innovation on these dimensions will drive rapid growth in demand for System Dynamics and its benefits.

Today System Dynamics practitioners are innovating on three key and primarily non-technical dimensions: 1) Collaborating; 2) Industrializing; and 3) Secularizing.

Innovating by Collaborating. There are three forms of collaborative innovation critical to System Dynamics: methodological; interpersonal; and interorganizational. Dynamic Monte Carlo simulation is an excellent example of market-opening methodological innovation. The two analytical methods synergize in ways that make each more powerful, and their combined and thereby enhanced characteristics are one key to solving the combinatorial explosion problem.

Interpersonal collaboration is an essential form of innovation because, for now at least, good System Dynamics practitioners are necessarily deep and narrow specialists. In stark contrast, System Dynamics itself is hugely broad, almost universal in its applicability to various walks of life. A deep and narrow specialist, alone, struggles to find entry points in the extremely broad range of markets where System Dynamics is applicable. Furthermore, System Dynamics work requires good access to market-specific knowledge and information. Collaboration with sector experts makes the unique skills of System Dynamics practitioners transportable between sectors. It reveals the same dynamic problems occurring in very different markets and enables proven simulator content to be reused to everyone's advantage. Collaboration allows synergistic blending of complementary skills, such as System Dynamics modeling and organizational change management. As in animal husbandry, cross-coupling strong strains tends to produce even more robust offspring.

Interorganizational collaboration is like interpersonal collaboration on steroids. It allows the blending not just of skills and knowledge, but of broad organizational capabilities in combinations that are far more powerful than the sum of their parts. It should enable System Dynamics models to serve as unusually effective brainpower transplanted (along with complementary brainpower from other disciplines) into unusually powerful market-focused bodies. These organizational hybrids will be capable of things that could not be imagined otherwise. Collaborative innovation of this sort is beginning and will permanently change existing markets and open big new ones.

Innovation by Industrialization. Good System Dynamics practice requires a high level of skill, and that traditionally takes a long time to acquire. A new practitioner gains skill by hands-on apprenticeship under more experienced practitioners, beginning with simpler tasks, models and analyses and progressing on to more challenging applications. This is an ancient approach to developing mastery of a challenging craft, and it has been employed in System Dynamics since the very beginning – some say that during the early days it took longer to get a PhD in System Dynamics than in any other discipline at MIT. Professor Forrester's early graduate students worked and learned the System Dynamics craft in an environment that has no equivalent today, and they developed a breadth of experience and depth of expertise that few of today's practitioners could match. This guild-like approach to training future masters in their craft was critical when the foundations of System Dynamics were being laid, and is likely to play a critical role again in the not-too-distant future. Ironically, its resurgent importance will be due in large part to the industrialization of System Dynamics that has been underway for some time.

Automobiles demonstrate the complementary yin-and-yang power of craftsmanship and industrialization. Early automobiles were hand-made by master coach-builders, men who had spent decades learning their craft. They were quite beautifully crafted and often just as unreliable as they were beautiful. Henry Ford changed all that by innovating, industrializing car-making based on standard parts, standardized manufacturing and assembly processes, and job specialization within those processes. Ford didn't invent industrialization – it had emerged in the 1840's in the valleys of Connecticut where it first transformed the design and manufacture of clocks, followed by firearms. Ford's innovation was to use the industrialization invention to transform the car-making process.

Innovation by industrialization transformed the skill-acquisition process, enabling high-quality work to be done by formerly unskilled laborers after a few months or even weeks of training. Innovation by industrialization transformed the work, the workers, the product and the market – with much narrower skills than their coach-builder forebears, the new workers produced far more reliable cars and earned much better wages that enabled them to purchase the product they produced! But that did not mean the death of craft-based auto production – today, largely because the auto industry industrialized, craft-based production is thriving as the source of the world's finest limited-production cars and of prototypes of mass-produced cars, and this on a scale that probably dwarfs the craft-based production before Ford. This demonstrates the natural complementarity of craft-based and industrialized processes.

Innovation by industrialization is just as applicable to System Dynamics as it was to automobiles, and it has been going on for some time. The first broad use of standardized model components came in the late early 1980s with discovery of Rework Cycle dynamics and their driving role in the performance of complex development projects. Those standardized components went on to prove their complete transportability, demonstrating consistently high and unprecedented levels of reliability on every type of complex project from shipbuilding to car development, from aircraft to civil construction, offshore oil platforms and even software projects. Today a similar set of standardized dynamic model components is demonstrating universality in commodity markets from the energy world to petrochemicals and finance.

Other elements of industrialization are accompanying use of standardized System Dynamics components. Some of the roles essential to best-practice System Dynamics can be better performed by role-specific specialists than by System Dynamics experts. Even for those roles requiring System Dynamics expertise, job specialization enables faster acquisition of critical skills and allows younger practitioners to make larger contributions much earlier in their careers. In turn, earlier exposure to more challenging work greatly accelerates their professional development. Standardized System Dynamics processes support younger practitioners in making larger contributions earlier. At the same time those standardized processes deliver more powerful and reliable simulators and analyses faster than used to be possible.

Innovation by industrialization is transforming management consulting based on System Dynamics. As it does, there is emerging a need both for the deeper learning experienced by Forrester's early graduate students and for the ability to invest in funding that learning. This need cannot be met by current models of consulting based on System Dynamics – meeting it requires further innovation. In short, industrialization of System Dynamics is not about abandoning our craft-based history, but embracing and extending it. We need both craft-based and industrialized structures, interwoven and mutually supportive – that is the innovation.

<u>Innovation by Secularization.</u> This paper began by describing my revelatory meeting with Jay Forrester and its transformational power. It also ends with that theme, because the same almost religious attraction is what drew so many of us to System Dynamics and what has kept us in it. That powerful attraction is not confined to those of us who were introduced to it thirty years ago. For many years I have participated in hiring students to work in System Dynamics. I see the same gleam in their eye, the same sense of inspiration and mission, that drew me to it. We've often said that about one in ten students has "IT", a certain something that told us they had caught the bug and would be good at System Dynamics. We couldn't define IT, but we were pretty good at recognizing IT when we saw IT, because it was like looking in the mirror.

In recent years I've been seeing that IT is also to be found in people who didn't learn System Dynamics at Sloan or LBS or LSE. IT is much more abundant than I had supposed – that 10% ratio seems to apply far outside the walls of MIT. IT can be found in people who have never heard of System Dynamics, and in people who acquired their knowledge of System Dynamics through other than traditional sources. We're learning, for example, that people with well-developed programming skills often have a mindset that makes them good candidates for System Dynamics work. Some of these people can be infected with IT and do very well.

Through this learning process we're being weaned away from dependence on the handful of institutions and processes that used to produce all System Dynamics practitioners. It's not that we've abandoned those institutions and processes, because they're still great. It's just that we've discovered new institutions and new processes and through them are meeting excellent people who are fast becoming strong contributors. Industrialization is every day making it easier for such people to find and join us, and this new blood is a very good thing. I think of this as innovation by the secularization of System Dynamics. For System Dynamics secularization doesn't mean the loss of our religious fervor or sense of mission, which are vital. It means broadening our view, including new ways of thinking about and using System Dynamics, new ways of including people from other disciplines and what they know that can expand the reach and value of System Dynamics. These people are much more than force multipliers, they are helping to move System Dynamics to a whole new energy level.

Looking at these additional, non-technical dimensions of innovation, we can perhaps see why System Dynamics is not yet at the center of a much larger market for non-traditional, which is to say dynamic, analyses. It isn't because there's any deficiency in System Dynamics or in the way it has been practiced and applied. It isn't because the wider world lacks the ability to understand or benefit from System Dynamics. It's actually inherent in the nature of knowledge-based innovations. Peter Drucker said it best in his ground-breaking book titled <u>Innovation and Entrepreneurship</u>.

> *"Knowledge-based innovation has the longest lead time of all innovations…[this] seems to be inherent in the nature of knowledge. We do not know why…"*
>
> *"…knowledge-based innovations…are almost never based on one factor but on the convergence of several different kinds of knowledge, not all of them scientific or technical…In most cases, the innovation occurs only when these various factors are already known, already available, already in use someplace…But*

*until all of the knowledges needed for a given knowledge-based innovation have come together, the innovation will not take off…Then suddenly there is a near-explosion…"*

System Dynamics alone is an invention of incredible analytical power. As System Dynamics coalesces with other technical and non-technical knowledges and inventions, there is emerging an innovation of incredible reach and power meeting much wider needs of the wider world. As this happens, System Dynamics will realize the world-reshaping potential that so many of us have always seen in it.

## Conclusion

For thirty years System Dynamics has made my professional life challenging, fascinating, rewarding, sometimes frightening, and never, ever dull. I am privileged to be a contributing member of one of the world's scarcest and most important groups of knowledge workers. And I can see innovation reshaping what we do and how we do it at a steadily accelerating pace, so that in less than ten years System Dynamics and its position in the world will be transformed from what we have known and become accustomed to. Recognizing needs as defined by the wider world is enabling us to innovate in new approaches to decision-making based on connectedness and in solving the multiplicity of "combinatorial explosion" problems around the world. Supporting components of that innovation include synergistic combinations – of System Dynamics with other analytical methods and of different skill groups and organization types – along with industrialization and secularization that are changing how we practice and how we grow the field. Innovation is not wiping out or replacing what we have known, it is building on and out from it to reach a range and level of influence that many of us expected and hoped to see long ago, and to accomplish things that we haven't yet dared to imagine.