Fons et origo: reflections on the 60th anniversary of 'Industrial Dynamics'

NOTES AND INSIGHTS

Fons et origo: reflections on the 60th anniversary of *Industrial Dynamics*

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Abstract

This paper records and reflects on the anniversary of the publication of Forrester's *Industrial Dynamics*. It considers the book from four perspectives. First, it samples the earlier publications that heralded and anticipated its publication. Second, it explores in depth some contemporary reviews, drawn from a range of disciplines. The paper then looks in detail at how the book was influenced by, and itself influenced, three neighbouring areas: MS/OR, system science and the social sciences, and 'problem structuring methods'. Fourth, to further place the book in context, the paper considers in brief the varied life of Forrester himself, indicating how his experiences informed *Industrial Dynamics*. The paper closes by recapitulating the importance of *Industrial Dynamics* as the founding publication of the system dynamics field.

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Introduction

Six decades ago Jay Wright Forrester's book *Industrial Dynamics* was first published (Forrester, 1961b). Of course, developments, ideas, and innovations have advanced and will continue to advance the field in the future. Nevertheless, it is hard to overstate the significance of this publication. It is the founding work of the field, the "source and origin" of its aspirations, general approach, and many of its specific elements. The name of the new field became more generalized later in the 1960s (see Appendix A) but there can be no doubt that this book is of unparalleled importance to system dynamics (Figure 1).

It would not be appropriate for the readership of this journal to describe in detail the book's contents. To position this paper, the following may suffice. The book was presented as an Introduction followed by 21 chapters organized into four parts, and 15 appendices. It ended with a terse 25 references (three of which relate to system dynamics work). In broad terms, it described modelling which involved feedback mechanisms, experimentation using computer simulation models, and the aim of doing policy analysis.[1] But those are, in a way, second order points. Of first order is the way Forrester argued that such models should be used—and how that usage can correct what he saw as

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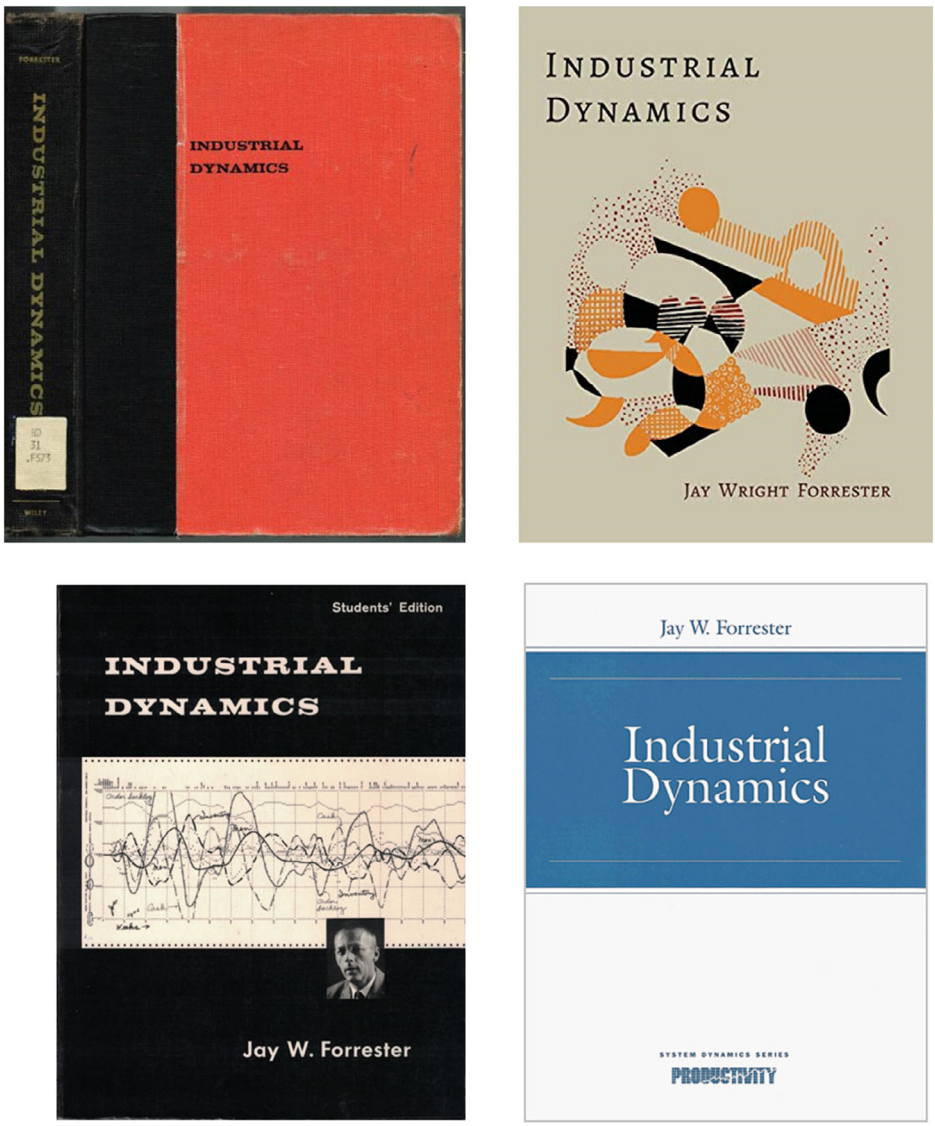

Fig. 1. Versions of *Industrial Dynamics*. The upper left image shows the spine and front board cover of the first edition. Note the added Dewey classification number. The design of the dust jacket is not certain — MIT Press has no record. Other images show later editions. Note how the "Students' Edition," 11th printing from 1985 (lower left) shows both simulation output relating to inventory oscillations and the author [Color figure can be viewed at wileyonlinelibrary.com]

profound errors in the aspirations and usage of current modelling approaches. *Industrial Dynamics* argued for modelling underpinned by the ideas of:

- models as representations of the mental models of decision makers;
- model validation as a process having both objective and irreducibly subjective elements; and
- the never entirely finished process of model building and experimentation as a provider of learning experiences.

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Together, Forrester argued, these could create a revolution in management, leading to a true "management science." That was the aim of the field of industrial dynamics — and of *Industrial Dynamics*.

This paper reflects on the 60th anniversary of the book by considering it from a number of perspectives. The first perspective concerns some immediate antecedents, papers that show Forrester's assembling the ideas of system dynamics. The second examines contemporary reactions to the book, looking in some detail at five significant sources. The next section considers *Industrial Dynamics* from the perspectives of management science/operations research (MS/OR), system science, and problem structuring methods, exploring how its ideas connect to thinking in those neighboring disciplines. A fourth perspective serves as a reminder of how the varied fields, accomplishments, and experiences of the man himself can be seen reflected in the pages of Forrester's book. The paper closes by commending *Industrial Dynamics* as a source of insight to all interested in the field.

Limbering up

Considered in its broadest terms, *Industrial Dynamics* draws ideas from many places, some of which are explored in later sections. Here we consider the more immediate antecedents, papers which began to bring together the ideas that specifically heralded that book. Table 1 summarizes the publications examined.

Forrester was appointed Professor of Industrial Management at the new Sloan School of Management in 1956 (MIT News Office, 1956). He was initially unclear what to do with his new role (Forrester, 1992). Chance, or fortune, entered the scene in the form of the management of General Electric who asked for advice concerning the chronic inventory oscillations experienced by the company in their Kentucky plant. Forrester has described how a simulation done on paper of a model which used feedback ideas from servomechanism theory offered an explanation for the counter-intuitive behaviour over time that GE was trying to deal with (Forrester, 1992).

What followed can be seen in Forrester (1956/2003). Viewed today as the first of the "D-memo" series, this remarkable, 27-page document looked at existing managerial modelling attempts and proposed a new approach. It generalized the GE experience to propose a form of modelling applicable to a wide range of social systems. It covered technical details but also the overarching rationale of using computer simulation (rather than mathematical "explicit solutions") based on "closed loop systems," time delays and nonlinear relationships. Whilst referring to the GE inventory case, it also contained an analysis of the dynamics of advertising. This is a key work in the field, and much of this material, and all of the underlying ideas, appear in *Industrial Dynamics*.

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Table 1. A selection of Forrester publications that are antecedents to *Industrial Dynamics*. See text for detailed links to the book

Date	Title & Source	Content
1956	*Dynamic Models of Economic Systems and Industrial Organizations* - Note to the Faculty Research Seminar or "D-memo zero"	• Technical exploration of deficiencies of existing modelling approaches • Proposes simulation of "closed loop systems" as approach to management • GE oscillations & advertising examples
1958	*Industrial Dynamics—A major breakthrough for decision makers* - Harvard Business Review	• Brief treatment of simulation as a new approach • Application to GE—"Bullwhip Effect"
1959	*Advertising: A problem in industrial dynamics* - Harvard Business Review	• Dynamic analysis of the effects of advertising campaigns
1959	*Management and Management Science* - MIT D-memo 48	• Draws on Drucker (1959) to critique current use of modelling by management • Proposes shift in management from "art" to "science" • Positions modelling as an approach for planning, experimentation and learning
1960	*The Impact of Feedback Control Concepts on the Management Sciences* - Foundation for Instrumentation Education and Research Distinguished Lecture	• Elaboration of D-memo 48 (item above) • Rejects 14 "obvious truths" about existing modelling approaches • Proposes modelling based on "feedback control concepts" as tool for helping leaders learn about their complex world
1961	*Standard Symbols for Industrial Dynamics Flow Diagrams* - MIT D-memo 41-1	• Proposes conventions for representing conserved flows, information flows, auxiliaries and stocks (including different orders of delay)

Forrester had sufficient confidence in these ideas to write an account of the GE work, combined with a brief outline of his new approach, in a journal article. Published in *Harvard Business Review*, its title held back nothing in announcing the appearance of a new field: "Industrial Dynamics—a major breakthrough for decision makers" (Forrester, 1958). The paper was later described as "widely acclaimed in managerial circles" (Battersby, 1963, p. 99). Whilst *Industrial Dynamics* is frequently cited as the source of the "Bullwhip effect," or "Forrester effect," it would be more correct to cite this

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piece. The paper is also noteworthy for its series of beautiful diagrams of simulation model output—subsequently re-used in *Industrial Dynamics* and admired by Battersby (see below). This case appears in Part III, one of the "Examples of Dynamic Systems Models."

A fully-developed version of the application of "Industrial Dynamics" to advertising appeared the following year, also in *Harvard Business Review* (Forrester, 1959a). This case is also treated in Part III of the book.

That same year came a D-memo which offered Forrester's views on the current state of management thinking and how new ideas can create a "management science" worthy of that term (Forrester, 1959b). The link to *Industrial Dynamics* is remarkable, rising immediately from the pages. Although the material is in a different order in various places, and not all is present, this memo is essentially the Introduction ("Management and Management Science") of *Industrial Dynamics*. For example, it contains a very similar threesome of diagrams (see Figure 2 for one example) and many passages are identical, for example, "Management is in transition from an art" (p. 3 in the memo; p. 1 in the book). Of its 11 references, eight are in *Industrial Dynamics*. One of these is a paper by Drucker (1959). This cites Forrester's 1958 article and may be part of the "acclaim" to which Battersby referred. It appears to have been a strong influence on this memo—a point discussed later.

The 1959 D-memo generated a piece appearing in 1960, also an important part of the story but different in style (Forrester, 1960/1975). This was apparently a paper delivered at the annual board meeting of the Foundation for Instrumentation Education and Research as that year's "FIER Distinguished Lecture." The venue is significant. This bold and wide-ranging piece presented industrial dynamics as a new way of modelling, based on "feedback control concepts," a new way of thinking about management and economics, and a new way of helping leaders learn about the complex world in which they live. It was also partly a report of applications of the approach by MIT Sloan Fellows. More broadly, it was a public version of the earlier D-memo, offering a new way of undertaking management as a "science" and a list of 14 "obvious truths" about modelling that Forrester specifically rejected.[2] As a statement of intent for the field it was a significant piece and some of its ideas also appear in Part I "The Managerial Viewpoint" and Part II "Dynamic Models of Industrial and Economic Activity."

Moving right up to the year of publication we find a memo on the symbols to be used for representing model structure—"flow diagrams" (Forrester, 1961c). The conventions are essentially identical to those in Chapter 8, "Symbols for flow diagrams" (see Figure 2).

Not all of the D-memos relevant to the book were by Forrester and certainly not all of their content was included. An example of both is Pugh (1957). This "delay response" analysis clearly informed Chapter 9 "Representing Delays" and Appendix H "Delays" and conceptually identical figures of "exponential-delay responses" appear in the book (Figure 3). However, Pugh used a mathematical approach, considering the effects of the delays as integrals and as Laplace

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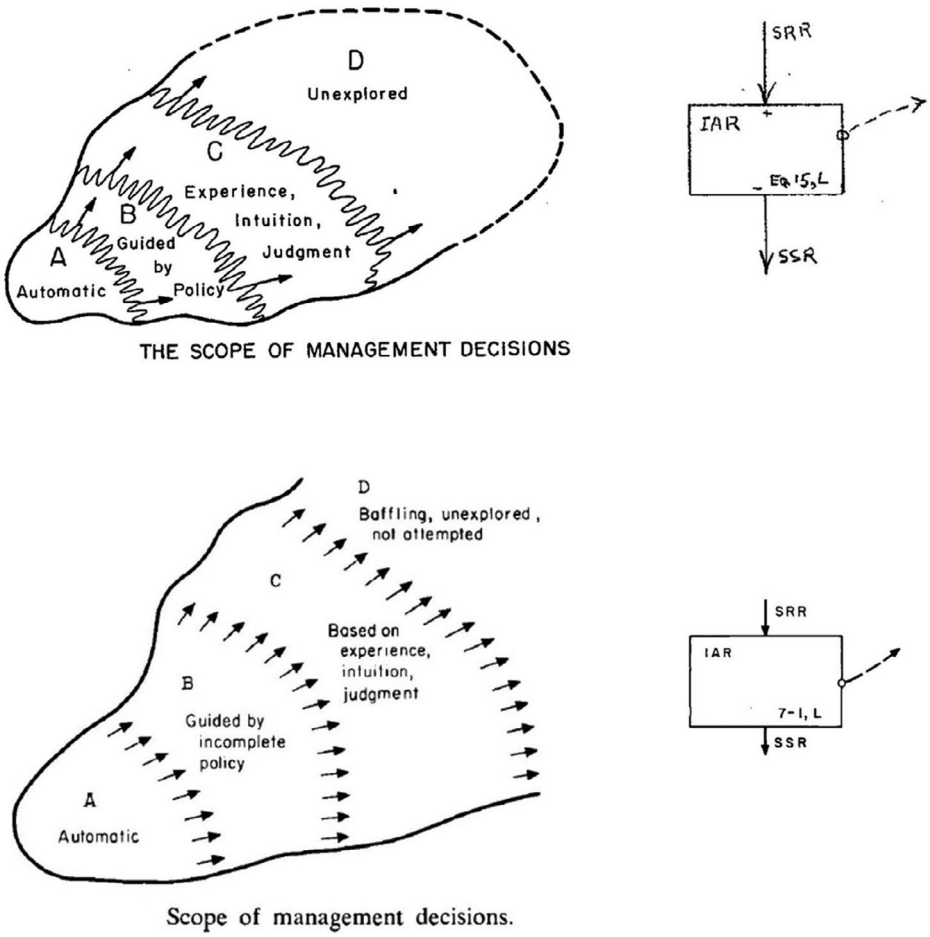

Fig. 2. Examples of diagrams from earlier D-memos and then from *Industrial Dynamics* revealing similarities and differences. Left: "Scope of management decisions": D-memo 48, p. 3 (top), and *Industrial Dynamics*, p. 6 (bottom). Right: "information take off from a level": D-memo 41-1, p. 4 (top), and *Industrial Dynamics*, p. 83 (bottom)

Transforms. This relates to Fey's comments about the origins of system dynamics referred to later. It also creates a valuable link to the work of Erlang (Krarup, 2004). This is unusual to see in the system dynamics literature. Whilst "systems mathematics" became part of the MIT course and included such analysis, even Forrester's more technical treatment (Forrester, 1968d), whilst having some integration, used no transforms. Of course, all of this material would have been familiar to him from his training in electrical engineering and also servomechanisms. The point is that none of the mathematical analysis in Pugh's memo appears in *Industrial Dynamics*. Rather, simulation is used. This may indicate a judgement by Forrester on the background of the intended readership—general management.

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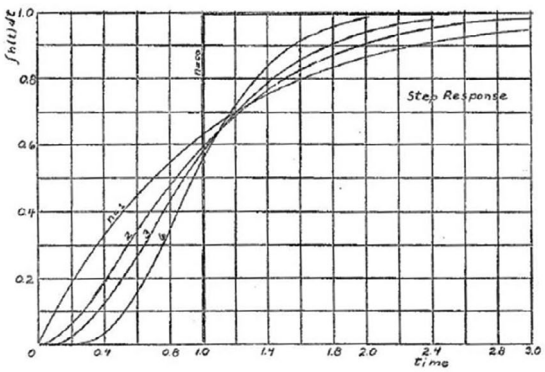
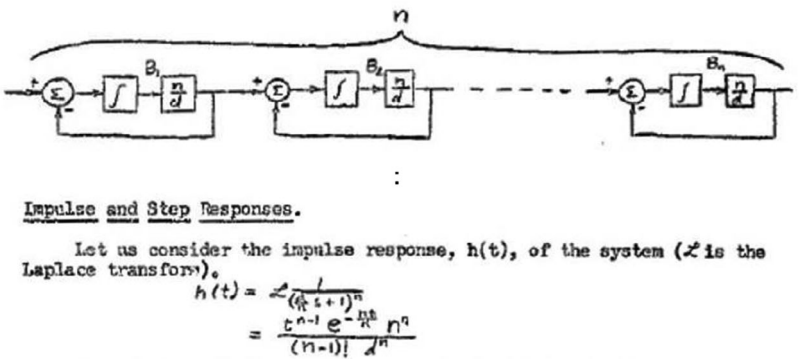


Figure 9-8 Exponential-delay responses to a unit-step rate.



Impulse and Step Responses.

Let us consider the impulse response, h(t), of the system ($\mathcal{L}$ is the Laplace transform).

$$h(t) = \mathcal{L}^{-1}\frac{1}{(\frac{n}{k}s+1)^n} = \frac{t^{n-1}e^{-\frac{nt}{k}}n^n}{(n-1)!\,k^n}$$

Fig. 3. Examples of comparison of content of D-memo 7 (Pugh, 1957) with *Industrial Dynamics* indicating similarities, differences, and absences. Top: "exponential-delay responses" from D-memo, p. 4. Note the integral sign, upper left. Middle: "exponential-delay responses" from *Industrial Dynamics*, p. 92. Compare with the above diagram. Bottom: "N cascaded exponentials" response to a step change, diagram and analysis: D-memo p. 3. There are no such diagrams or associated mathematical analyses in *Industrial Dynamics*

In closing this section it should be noted that although it aims to treat the main public publications, it can only sample the D-memos published within MIT. Further work is required here.[3] Nevertheless, the publications discussed above are significant markers on the route to *Industrial Dynamics*.

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Contemporary reactions

Reactions to publication came from various sources. Five are considered below.

Reaction from The New York Times

A reaction that took the longest to appear is interesting both because of its source and because of the scope of its comment. In early 1964, in an article in *The New York Times*, John Platt, physicist, biophysicist, and philosopher of science, then at the University of Chicago and later to become involved in the Club of Rome, described his attempt to compile a student reading list. He consulted a range of colleagues for

> …seminal books of the last 20 years or so … the kind that might possibly be of maximum significance as 'source books' for the shape of society in, say, 100 years. Books that, as far as we can now guess, might be comparable in ultimate importance to, say, Galileo or Malthus or Rousseau or Mill.… [Books] that ought to have the widest readership — not only by laymen but by scholars and scientists in different fields. (Platt, 1964, p. 6)

Platt then mentioned books by Wiener, von Neumann, Galbraith and Keynes, Ashby and Shannon, Huxley and Mead. He quoted the concern of one of those he consulted, "I'm struck by how few non-Americans (including refugees) are on my list. I'm sure this means ethnocentrism," and the view of another who cast doubt on the project itself: "Very few of the books I've mentioned seem to me as important as Freud or Marx or Galileo" (p. 6). Perhaps, then, this piece should not carry too much weight. Nevertheless, he had given to his students a list of "Men [*sic*.] who are going to play major roles in the creation of our future" (p. 30). In his penultimate paragraph the following comment is found: "They should know Jay Forrester's *Industrial Dynamics*, on feedbacks and fluctuations" (p. 30). Thus Forrester's work becomes a member of Platt's list of "Books That Make a Year's Reading and a Lifetime's Enrichment."[4]

Reaction from Operational Research

The *Operational Research Quarterly* is today's *Journal of the Operational Research Society*. The reviewer there records that *Industrial Dynamics* was priced at "£6 15 s. 0 d."

The reviewer was Cranfield University's A. Battersby (1963). He noted the "readable style … sometimes approach[ing] prolixity" and welcomed the quality of printing and binding, and also the "two-color diagrams" (p. 101). In substantive terms, the core of his reaction was highly supportive. We turn to this in a moment.

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However, let us first consider the criticisms. Battersby was unconvinced by the argument that judgmental estimates of parameters are sufficient to get a simulation running, and that the simulation can itself then be used to explore the need for greater accuracy in parameter values. He thought that Forrester "approached the problem of evaluating the parameters in a somewhat cavalier fashion," advancing a "dangerous doctrine" (p. 100), and gives an argument that deserves engagement. A further "source of disquiet" (p. 100) was what he saw as inconsistencies in assumptions about operating policies in the inventory case study. Based on the fact that Forrester allows himself this, Battersby accused him of having "fallen in love with his theory" and exhibiting the "Galatea complex … the urge to conceal or excuse the loved one's blemishes and short-comings" (p. 100). Lastly, Battersby gave a sound critique of what he saw as Forrester's false assertion that forecasting tends to ignore the effects of a forecast. He cited an example—not to be found in *Industrial Dynamics* — in which "feed-back effects" are discussed (p. 101). These criticisms are thoughtful and still merit attention.

None of which detracts from the core message of the book review. Here Battersby spoke to a chasm in OR approaches, one that remains an object of contention today. He saw two "factions" in OR, "Optimizers" and "Meliorizers." "Optimizers" concern themselves with explicit mathematical solutions, for which elegance, completeness and, most of all, generality are the prized features. In pursing the "best way," they see simulation "as a confession of failure" (p. 98). He differentiated these from operational researchers seeking a "better" ways of doing thing. He calls them "Meliorizers," from the Latin *melior* meaning "better." They see simulation as a powerful tool for making things better, for discovering improvements. From this supportive reaction we may learn, therefore, that system dynamicists are "Meliorizers" who call for "clear logical thinking rather than mathematical refinement" (p. 101). Battersby stated unequivocally, "Professor Jay Forrester of M.I.T. is a downright and uncompromising Meliorizer" (p. 99). He quoted at length from the opening of *Industrial Dynamics*, where Forrester surveys and critiques "The Manager and Today's Management Science" (Forrester, 1961b, p. 3).

Battersby was very aware of the advantages of that stance, its rejection of mere "formal logic" and the worthlessness of establishing analytically the optimum "of a representation so circumscribed and artificial that any resemblance to physical reality is fortuitous" (p. 99). He particularly praised Forrester's ideas for broadening the scope of "system boundary" and their ability to deal with the "open systems" which he saw as characterizing "higher levels of management activity." Though not using the word, Battersby was praising Forrester's interest in endogeneity — and he clearly and explicitly grasped the special importance that *Industrial Dynamics* gives to understanding "The structure of the system rather than its parameters" (p. 100).

There is much overlap here with the critique of MS/OR that emerged in the late 1970s and early 1980s and the resulting debates about the nature of

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MS/OR. Whilst that debate continues today (and is discussed further in the next section) Battersby's reaction indicates that *Industrial Dynamics* stands as a precursor to it and it is interesting to see this debate invoked in the early 1960s and in the name of industrial dynamics.

Whilst Battersby was clearly not entirely convinced, he strikingly concluded:

> in spite of these drawbacks, this is an important book, possibly even an indispensable one.… There is a strong artery of common sense running through it, a heart of enthusiasm driving it and a backbone of achievement supporting it. No intelligent student of management problems can fail to be rewarded and perhaps inspired by much of it. (p. 101)

Reaction from Management Science

In his review in *Management Science*, Harvey Wagner of Stanford University started intriguingly by describing the book as "a gigantic addition to management science" because of its "sheer physical dimensions … selling price[5] … scope … brilliance of execution … and its self-satisfaction" (Wagner, 1963, p. 184). Labelling himself as an "economist turned operations researcher," he saw many points that he could argue with—but then decided to avoid "polemic argument." We are left only with his wondering fleetingly whether *Industrial Dynamics* will:

> …be credited with providing the missing link between the grand conceptions of classical Continental economists and the imaginative inventions of modem electronics wizards. (p. 184)

With the application of system dynamics to economic issues still very much a work in progress, his decision deliberately to exclude what might well have been his most important reaction is unfortunate. That perspective would be interesting to know and to revisit today. However, what remains is insightful.

Wagner outlined the contents. He praised chapters on how models should be used, commenting that they offered insight on problems with existing model usage and recommended that "every serious student of management science" should read them (p. 184). He accurately discerned the core interests as being causative structure, nonlinearity, and the aspiration to deal with problems of planning, to study "different strategic configurations of management systems" (p. 185) and to provide insights. In a striking phrase, he described how:

> At the press of a computer button, Forrester listens to the heart beat, checks the respiration rate, and measures the reflexes of a firm as well as any fully outfitted medic does his ailing patient. (p. 184)

However, he saw as a "serious imperfection" the book's failure to consider the effects of "stochastic elements." At greater length he expressed concern

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that "planning models" can never be completed. This second observation clearly overlooked the nascent industrial dynamics ideas about models as contingent entities, ideas discussed later in this paper. Instead, Wagner saw the book through the lens of hard systems analysis; this is why he doubted that a model could ever achieve "validity," could ever be a "sufficiently accurate representation."

Finally, he wondered whether industrial dynamics is such a concoction of elements that it could only be used by Forrester and those very close to him. Strangely, he ended his thoughtful review by suggesting that if that were so, "then *Industrial Dynamics* is an even greater tribute to one man's genius" (p. 186).

Reaction from Science

We have a second voice from Stanford University, since the journal *Science*, published by the American Association for the Advancement of Science, had Donald Porter review *Industrial Dynamics*. With one significant reservation, he was impressed (Porter, 1962).

His concern—"This book's major shortcoming" (p. 426)—is that it offered no evidence that the approach it advances had actually done any practical good. He saw a "lack of confirming data" (p. 426), "no evidence of … efficacy" (p. 427). A significant reservation indeed.

Yet Porter described the book as "a radical new and different approach" and "a very exciting beginning" (pp. 426–427). Why? Because he was attracted by the idea of an approach that looks across different functional areas of management. He approved of the use of computer models to do this and, in an echo of Battersby's remarks in *Operational Research Quarterly*, saw it as a strength that Forrester "has not succumbed to the current craze of mathematical elegance for the sole sake of elegance" (p. 426). What comes through most clearly is his understanding that the approach can reveal what system dynamicists would call "unanticipated consequences," or "counterintuitive effects." In his own words, "The book provides the tools … to challenge old management clichés, myths and shibboleths—the author is an industrial iconoclast" (p. 426). He picked out example after example, revealing what feels like delight in the surprising insights that are offered.

Porter's reaction ended by noting that he:

> looks forward to further development of the techniques described and particularly to more evidence confirming the ability of the models to accurately point the way to improved managerial performance. (p. 237)

Porter's firm grasp of the central ideas may be what lead him to look beyond the "major shortcoming" in this way. His challenge is consistent with

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Forrester's subsequent crowning of the "system improvement test" amongst his tests for building confidence in a model (Forrester and Senge, 1980). Indeed, that challenge merits constant attention. Usefulness is a touchstone for the field, perhaps its best argument in the face of demands for "mathematical elegance." Porter was quite wrong that this demand was merely a "craze" — it persists today.

Reaction from Management

A reaction to the book came very rapidly from the management perspective, at least that represented by the Academy of Management. In 1962 *Industrial Dynamics* was one of five recipients of its McKinsey Foundation Book Award (Editors, 1963). The awards were given at a lunch held at the University Club in New York City on 28 January 1963 and this was followed by a panel discussion by the award winning authors on "What Has Happened to the Management Movement in the United States" (p. 90).[6]

This was the inaugural year for these awards. Winners were selected by a Board of Judges drawn from universities and industry (Anon, 1963). The actual criteria for the award are quite lengthy but their general tone is conveyed at the beginning of the "Criteria of Eligibility":

> The prime objective of the Academy of Management Book Awards Program is to recognize examples of books which contribute significant insights, ideas, information or concepts to managers with major policy responsibilities.
>
> In meeting this objective, the concept here is that the award-winning books will advance the actual practice of management in industry, commerce, and other institutions. They will especially facilitate such practice to meet constantly higher professional standards. (Editors, 1966, p. 379)

To offer some specific comparison, only two years later Forrester's book was joined on that list by Peter Drucker's *Managing for Results* and by Alfred Sloan's *My Years with General Motors*. The presence of *Industrial Dynamics* is noteworthy. Though it is not the only winner with "technical' content — William Morris's *Management Science in Action* was a winner in 1963 — most of the publications recognized by the Academy in the first three years of the scheme are more descriptive in their style. For *Industrial Dynamics* to be included here would seem to say something about the favorable reaction to Forrester's aspirations regarding the nature of management thinking and the contribution that simulation could make to it.

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Neighbouring disciplines

At the 1996 International System Dynamics Conference, Willard Fey used the 1956 "D-memo zero" as a temporal prompt to offer a "Forty Year Retrospective." In his plenary he commented, "It is important to understand we don't just rely on Jay but on science." I recall his describing how Forrester's ideas emerged from a broad hinterland of knowledge, and citing Leibnitz's use of an integral approach to calculus and Laplace's creation of the Laplace Transform as elements of this hinterland. These ideas are developed further in Fey (2002). The intellectual basis of *Industrial Dynamics* is indeed broad. This section concerns its relationship with three areas of thought with which it had and still has considerable affinities. It explores these in terms of intellectual provenance, similarity, and influence.

System dynamics and MS/OR

When he joined the Sloan School in 1956, Forrester wondered what he could contribute to a management school created in a technical environment. Casting about for sources of inspiration, he examined the field of MS/OR. In a backhanded compliment, he later observed that it "did pay its way" but did not deal with "major [problems] that made the difference between the companies that succeed and those that stagnate or fail" (Forrester, 1968b, p. 399). A similar reaction is seen in his remark, "Operations research has been evolving for 15 years. It has still not broken into the inner circle of top management" (Forrester, 1959b, p. 15). However, that D-memo appears to have been influenced quite considerably by one of its references, namely Drucker (1959). That paper explored the prospects of management science, based on "the last four or five years of literature" (p. 25). Drucker thought that the potential of management science "is in danger of being frittered away" (p. 25). He offered deep criticism of the area and thoughts on how to correct these. Drucker cites "industrial dynamics" and Forrester's 1958 *Harvard Business Review* article as one of only two instances of work he considers useful for managing an enterprise in its totality. The link to *Industrial Dynamics* is remarkable. There is a story yet to be teased out about the back-and-forth influencing amongst these two highly significant management thinkers. Drucker's view on management and the failings of management science would certainly appear to have had a very significant influence on Forrester's disciplinary positioning of industrial dynamics—and hence on the thinking of all system dynamicists today. This is a noteworthy finding.

This context helps explain why Forrester definitively stepped away from MS/OR. Indeed, for decades afterwards, system dynamics held itself separate from the institutions of MS/OR. This may seem an odd move. The underlying intellectual connections between the ideas in *Industrial Dynamics* and MS/OR are considerable: There is a shared belief in the use of models to

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improve the world. Why, then, was "industrial dynamics" presented as an activity mostly separate from the institutions of MS/OR? Why did system dynamics for so long preserve that separation?

An understanding of the nature of the two fields in the late 1950s and early 1960s illuminates both questions. Drucker—an astute outsider—understood the state of things very well. Some insiders were of the same view. At the time, MS/OR meant "Hard OR": a technical approach to narrowly defined problems. That approach was ultimately the subject of serious criticism from one of the founders of MS/OR: Ackoff argued that a concentration on optimization and mathematization undercut attempts to solve all but the most narrowly defined "problems" (Ackoff, 1977, 1979). Instead, he championed interdisciplinary approaches to tackle the "messes" that arise in the real world (Ackoff, 1981).

Forrester's ideas went considerably beyond the aspirations, style, and practical use of what was then MS/OR. If that field could be characterized as technical, narrow, and optimizing, then Forrester's ideas were about simulation, breadth, and improvement. Referring back to Forrester's 1958 paper, one operational researcher wondered whether it gained approval "because his summary of the shortcomings of management science was timely and true" (Battersby, 1963, p. 99). Similarly, an "Operations Researcher" refers to the book's "sage observation about many deep conceptual problems in management science" (Wagner, 1963, p. 184). Forrester was aware of these shortcomings. It would therefore have been hard to present industrial dynamics as part of MS/OR. Indeed, Forrester aspired to create a new field of "enterprise design."[7] In all likelihood, it was therefore a shrewd move, perhaps a vital one, to separate and to create the space for his approach to take flight. *Industrial Dynamics* challenged current thinking in various ways and it needed room to root itself and to flourish.[8] This detached approach allowed the subject of system dynamics to be launched and grow—but clearly separated it from the world of MS/OR.

MS/OR has quite a history of being worried about its own methodology (see Caywood, 1970; Zahedi, 1984; Sodhi and Tang, 2008). For example, the valuing of mathematical purism over the ability to address a real management problem with whatever rational analysis technique best fits the task at hand has long been a source of contention—and this continues (Ackermann and 46 others, 2009). However, the last two or three decades have seen those who employ the ideas in Forrester's book becoming increasingly consistent with parts of the field of MS/OR, whilst those parts of MS/OR have themselves reached conclusions which sit well with, indeed, which develop, Forrester's earlier ideas. Detailed argument for this may be found elsewhere (Lane, 1994, 1999), but strong connections between system dynamics and MS/OR are best seen in the areas of group modelling and "Soft OR," connections explored further below.

To close, three indicators of a reconnection of system dynamics with MS/OR are worth mentioning here. First, from Forrester, an observation that casts a light both on the initial separation and on the recent reconnection. Reacting to a description of "Hard OR" and "Soft" OR, he states that, "System

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dynamics fits the latter part of this description much better than the first part" and explains why (Forrester, 1994, p. 251). Second, MS/OR and system dynamics increasingly share an understanding that a "behavioural view" — of what should be built into models and of how one goes about using models — can make a significant improvements to both theory and practice (Lane and Rouwette, 2022; Hämäläinen *et al.*, 2013). Last, we have the view of the International Federation of OR Societies. In 2003 it launched an "OR Hall of Fame" to celebrate the pioneers and innovators in MS/OR (Rand, 2003). It currently contains 23 members. One of those now officially installed at the heart of MS/OR is Jay Forrester (Rand, 2006).

"Industrial dynamics" and systems science

The ideas in *Industrial Dynamics* posit actors in the various areas of any organization having policies which, moment by moment, generate streams of decisions. The consequences of those decisions then have consequences which flow across the organization, and may also return — feed back — as information to the original decision points. The behaviour over time of the organization results endogenously from these policies and their interconnected web. This is a systems view.

As stated earlier, quite an influence on Forrester's thinking seems to have been Drucker (1959). He saw the "business enterprise" as a "system" and emphasized the "performance of the whole" (p. 26). He made an explicit link to the work of Boulding (1956), a key systems scientist. Drucker also described how it might be better to "weaken" rather than strengthen part of a system (an interpretation of this in terms of loop dominance was surely natural to Forrester). In offering his call-to-arms for improving management science, Drucker was clearly drawing on a range of ideas from the literature of systems theory and cybernetics. What is significant is that he then approvingly cited Forrester's new approach of industrial dynamics as a significant departure from the narrow thinking he saw at the time, a move towards the systems ideas he thought valuable. The book *Industrial Dynamics* is partly a response to this call and systems science was therefore central to the aspirations for the field expressed in the book.

There are other direct connections with, and antecedents in, systems science. For example, to Wiener's (1948) control theories and Tustin's (1953) feedback study of economic systems — the latter being referenced in *Industrial Dynamics*. However, although the insight that we can usefully view the world as a system was not in itself new, the book offered a significant innovation. The more technical parts of systems science had not really managed to bring to life that systems view, that feedback view, in a practical way that would enable it to contribute to management thinking. What was needed was a vehicle that helped people to do something with that idea, a tool that helped them move forward. With *Industrial Dynamics*, computer simulation was that vehicle.

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Hence, Richardson acknowledges that similar thinking existed prior to Forrester and he discusses two "threads" of "Feedback Thought" (Richardson, 1991). The "cybernetics thread"—exemplified in MS/OR by Beer's work—aimed to understand events and decisions by focusing on the role of feedback in processes of communication and control (e.g. Beer, 1959). In contrast, the "servomechanisms thread" placed prime importance on patterns of behaviour of feedback systems and the policies which produced these. He suggested that system dynamics generated an evolutionary leap in this "servomechanisms thread."

The links between *Industrial Dynamics* and the larger field of systems science (and its methodological debates) can also be explored from the perspective of social systems theory. This allows some misunderstandings of Forrester's ideas to be clarified and placed in historical context. The book takes an endogenous view of management problems, a social systems theory using a feedback view of the social world. Its approach might appear to be hard, objective, nomothetic, and almost crudely realist (the terms derive from Burrell and Morgan, 1979). However, further reading goes against this. The insistence that dynamics are likely to be disequilibrium in nature, and the interest in considering the flow and interpretation of information may be seen as a move away from objectivism and into the realm of "integrative social theory." Most important of all are those three notions of mental model representation, validation by confidence, and modelling as a learning experience.

This closer reading is needed because a criticism of *Industrial Dynamics* is that it offered a ludicrously technophile 1950s worldview which sought to engineer social systems as if they were natural systems. Hence, it is argued, only a subsequent "revolution" in the approach occurred to create the current version of the field.[9] This is not an accurate account.[10] There are much more subtle ideas in *Industrial Dynamics*, clearly present at the creation of the field. They are certainly not fully developed or even explored; however, they indicate a much more "interactionist" stance. As discussed in the next subsection, this stance was subsequently developed and made explicit (Lane, 2000; Lane and Husemann, 2008; Hovmand, 2014). This was, however, an evolutionary — not revolutionary — process, one that developed and built on the ideas in *Industrial Dynamics*.

Turning to the influence of *Industrial Dynamics* on systems science, this might be judged in two ways. First, its influence on system science itself is very significant. The most popular systems approaches in use today are surely system dynamics and Checkland's soft systems methodology. These have managed to break into other disciplinary areas and be used with great effectiveness.

A second, much more broad, way of considering the influence of the book is to view its effects on the social sciences themselves, the project of "Selling system dynamics to (other) social scientists" (*pace* Repenning, 2003). To take one example, sociology has an established interest in mathematical modelling (Coleman, 1963), attempts to employ a "systems approach" (for a review see Lane, 2001), increasingly uses forms of simulation (Jacobsen *et al.*, 1990; Gilbert and Doran, 1994; Squazzoni *et al.*, 2014), and calls for a more rigorous

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approach to theory building (Collins and Waller, 1994; Hedström and Swedberg, 1998). However, system dynamics is yet to provide the "Systemic Dynamic Social Theory" that has been called for (Hull, 1970, p. 355).

There are certainly distinguished works that apply system dynamics to central concerns in social science. Noteworthy examples include Forrester *et al*. (1976) and Forrester (1977, 1979, 2013) as well as Jacobsen and Bronson (1985) and Hanneman (1988). There is, of course, a range of more recent applications of system dynamics to problems across social science as well as the curated collection of works on *Social Dynamics* (Richardson, 2019) and the pendant and upcoming collection on *Economic Dynamics*.

Nevertheless, the potential is not yet realized; Repenning's project is still very much a work in progress. His two-decade-old description of the system dynamics community as "largely isolated from mainstream social science. While psychologists, sociologists, anthropologists and others struggle to make sense of a complex and changing world" still largely holds (Repenning, 2003, p. 322). The task — one undoubtedly implied by *Industrial Dynamics* — of "more tightly integrating SD with the social science mainstream" (*ibid*., p. 324) remains to be fulfilled.

To close, it is the systems perspective that further illuminates Forrester's dismissive remarks about MS/OR. His rejection of that field and his striking out to create a new one seems to have a basis related to the concerns raised by Drucker and by Ackoff. The latter was a long-term champion of the systems approach (e.g. Ackoff, 1974). Ackoff's view here was grounded in his observation that MS/OR did not adopt a sufficiently broad systems view and was therefore applied to "problems of limited scope" (Ackoff, 1961, p.31). He was speaking as one of the founders of MS/OR, advancing the case for a systems approach—and his comment was published in exactly the same year as *Industrial Dynamics*.

"Industrial dynamics" and the problem structuring methods of OR

Beyond the concerns of industrial dynamics with simulation, breadth and improvement, there are more specific features that relate the field to "Problem Structuring Methods" (PSMs) that began to appear in the 1970s (see Rosenhead, 1989b). These features concern the role and nature of the models that are used.

Concerning the role that models play, the importance attached to engagement with mental models in *Industrial Dynamics* is significant. This is the idea — elaborated in later publications (e.g. Forrester, 1971a) but clearly present in 1961 — that managers "playing" with a model together can discuss, clarify, learn, improve their intuition and create new mental models which become the shared basis for policy making. This idea of shared mental models pre-dates Mintzberg's work on "organizational memory" and the "organizational learning" work of the 1990s, whilst the notion of creative

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play with computers anticipates Papert's work on developing geometry skills in children using a programmable robot (Papert, 1980).

Here then is a first strong connection between Forrester's ideas and those of PSMs: the role of models. In PSM practice, models are seen as contingent entities, artefacts used to address particular concerns of a particular group at a particular time. The benefits of adding some form of rational structure to discussions, helping people give some shape to a problematic situation, are all emphasized. The central concerns are group participation and seeing the modelling process as a learning experience which creates commitment to real world action (see Checkland, 1981; Eden and Sims, 1981; Phillips, 1984). Such ideas are familiar to system dynamists today.

In fact, Forrester championed very similar ideas long before their detailed handling within the OR community. Although one would hardly expect these ideas in *Industrial Dynamics* to be identical to today's PSMs thinking, the roots of modern practice were clearly present in 1961. A later comment, from two historians of science, sees these aims very clearly: "Industrial Dynamics was not meant to be applied by mathematicians and technical specialists in consultation with managers, but by managers themselves" (Thomas and Williams, 2009, p. 245).

The form of group working practiced then was considerably limited by participants' ability to work easily with computer models. A brief glance at "Appendix A DYNAMO," with its examples of how model equations appeared, vividly makes the point. Considering the software available until the mid-1980s (Richmond, 1985), it is perhaps a testament to the power of the system dynamics approach that any of Forrester's consulting assignments managed to involve managers at all, let alone engage them and convey something useful. That they did, and that he identified these features as important aspirations, probably speaks of his personality and imaginative intellectual vision. But it also reveals the power and aims of the approach. Subsequent research has explicitly linked system dynamics with modelling by problem owners, modelling in groups, and also with relevant MS/OR research and the literature on group decision support (Richmond, 1987/1997; Reagan-Cirincione *et al.*, 1991; Lane, 1992; Vennix, 1996).

The second strong connection between Forrester's ideas and those of PSMs concerns the nature of the models developed. A "naïve realist" view says that systems exist in the world, that we can have knowledge of these "things in themselves" and models aspire to represent them. In contrast, PSM practice adopts a form of epistemic humility by which models are generally seen more as artefacts, ways of helping structure inquiry, tools that are useful for organizing one's thinking. As suggested above, similar ideas can be discerned — albeit in embryonic form — in *Industrial Dynamics*.

Support for this view is offered by Richardson: one of his list of "hidden gems" of Forrester's practice is " 'Systems' are imaginary. We don't find them, we conjure them" (Richardson, 2022). He provides various arguments in

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evidence, attaching particular importance to the fact that in *Industrial Dynamics* Forrester commences his steps in "enterprise design" with "Identify a problem" (Forrester, 1961b, p. 13). Richardson observes, "He never would have said 'Identify a system' — at that beginning moment, there isn't one".

However, in making the broader case about the nature of models, some caution is needed. It cannot be argued that Forrester committed to a Checkland-like categorical stance of "models are merely epistemological devices that help you think" (Checkland, 1992). He never got quite that far. Rather, Forrester's writings reveal a tendency to move back and forth in his positioning of models, with occasional collapse into naïve realism.[11] Nevertheless, in a stance both surprising and remarkable for the time and for a writer with an engineering training, I would argue that the weight of his writing does see models not as realistic representations but as useful devices for dealing with complex situations. This is striking.

That system dynamics took these two stances — on the role of models and on the nature of models — and that it was always concerned with the process of model building in groups and with the associated importance of experiential learning, has not always been understood. In fact, modern forms of "group model building" in the system dynamics field are a natural development of the field's earliest assumptions, a testament to the imagination and richness of the ideas in *Industrial Dynamics*. It is notable that these ideas in some ways anticipated the appearance of PSMs.

The prepared mind

Earlier in this paper Forrester's response to his chance exposure to the inventory oscillation at GE was referred to as "fortune." True — but the aphorism holds: "fortune favors the prepared mind."[13] Forrester's mind had been prepared by a striking journey in space and time and thought. Another way of looking at *Industrial Dynamics* is therefore to consider how that book's intellectual and attitudinal provenance is biographical, resting firmly on the personal knowledge, accomplishments, and experiences of Forrester himself.

That biographical imprint emerges when considering his own accounts (Forrester, 1990, 1992, 2001, 2002). That provenance has been explored in some depth previously, including on the pages of *System Dynamics Review* (Lane, 2006, 2007, 2010). Consequently, no lengthy account is called for here. Nevertheless, it is worth a brief reminder of the different strands of Forrester's life that wove successfully together in *Industrial Dynamics*, how the book shows a convergence of different elements of Forrester's thinking and the creation from them of a coherent whole, which resulted in system dynamics (see Figures 4 and 5). Its pages recall the experiences of decades; on them the following can be seen.

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Fig. 4. Biographical provenance. (Top left) Nebraska: "This is the ranch house with its 40-acre front yard where I grew up. It was taken about 1939. My horse, Roany, in the foreground is the one that I rode to the one-room country school house" — Forrester writing in 2007. (Top right) Purposeful electricity: "On the right is the 12 volt wind generator that I built while a senior in high school to provide the first electricity on our ranch. On the left is the windmill for water"—Forrester writing in 2007. (Bottom left) Servomechanism at war: USS Lexington CV-16, shown here after commissioning in Boston, 17 February 1943. (Bottom right) Aircraft Simulation: Assistant director of MIT's Digital Computing Laboratory Robert Everett, seated in the "Control Force Demonstrator" developed as part of the ASCA project, 1947. For all image credits see endnote 12 [Color figure can be viewed at wileyonlinelibrary.com]

- Forrester, the boy born on a Nebraskan ranch who rode a horse called "Roany" to school where he was taught by his own father, who learned about electricity by tinkering with doorbells, telegraphs, and batteries, and who brought electricity to the ranch by building a wind-powered generator — who then always held to the lesson that "life must be very practical. It is not theoretical, it is not conceptual without purpose. One works to get results" (1990, p. 2).
- The man trained as an electrical engineer, who understood the flow of current down wires and its accumulation in capacitors — who then formulated a method that uses flows and stocks.
- The servomechanisms engineer whose mechanical-hydraulic apparatus that continuously adjusted the tilt of a rotating radar dish to correct for

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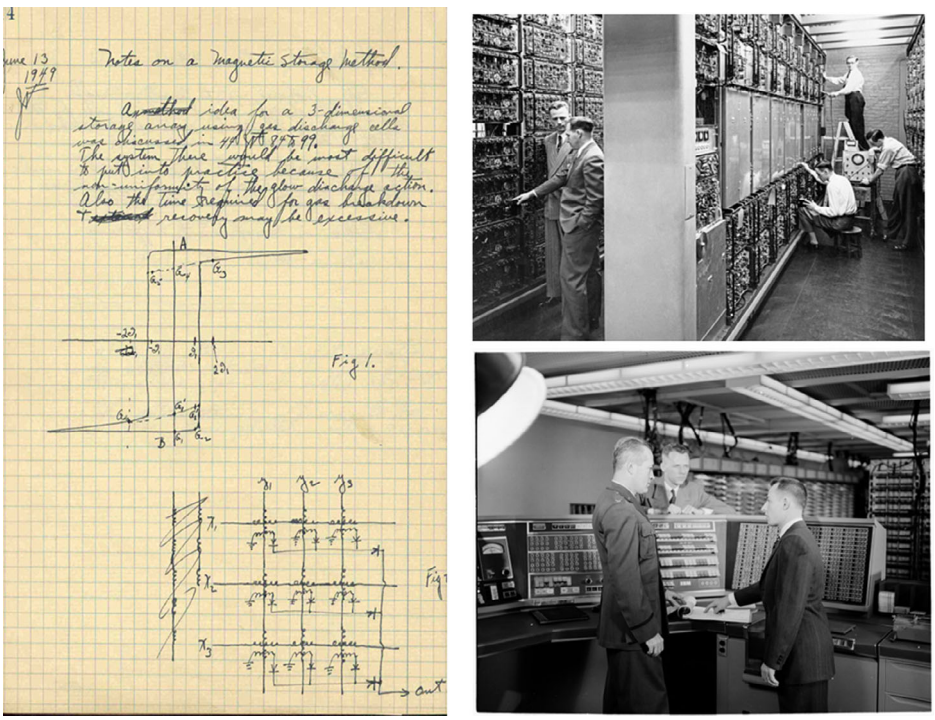

Fig. 5. Biographical provenance. (Left) Practical problem solving: Forrester's thinking on the way to inventing coincident-current magnetic core memory is revealed in his "Notes on a magnetic storage method," a page from his notebook, dated, 13 June 1949. (Top right) Digital computing: Forrester (far left) and others with the CPU of Whirlwind I (which occupied 224 linear feet of 10 foot racks), c. 1950s. (Bottom right) Defense project directing: Forrester standing behind a computer maintenance console, 15 February 1956. Note the military officer. For all image credits see endnote 14 [Color figure can be viewed at wileyonlinelibrary.com]

the rolling and pitching of *USS Lexington (CV-16)* helped teach him that a combination of positive and negative feedback loops could create complex behaviour — who then realized that similar collections of loops underlie the counterintuitive behaviour of social systems.

- The man whose time on the *USS Lexington* during battle reinforced in him the importance of practical, robust solutions — who then wrote of the importance of courage in tackling important problems.
- The ASCA (Aircraft Stability and Control Analyzer) project director who understood that designs for possible aircraft could be test-flown, the behaviour of the proposed aircraft learned about in a direct, experiential way, using digital computation — who then argued for organizational design using computer simulation.
- The Project Whirlwind director who realized that advanced digital computing was required to create those simulations of planned aircraft structures — who then suggested that computers could play a role in exploring ideas about complex feedback systems

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- The man who addressed the problem of poor reliability of electrostatic storage tube technologies in a practical and implementable way by inventing coincident coil magnetic core memory — who then continued to suggest ways of addressing important managerial and social issues with high-speed computing at the center of the endeavour.
- The SAGE (Semi-Automatic Ground Environment) defense system project director who experienced the challenges of managing a large organization whose goal was to create the AN/FSQ-7, the world's first computer produced in volume, a device that had the reliability to sit at the center of the USA's entire air defense system — who then crafted a useful, scientific approach to managerial policy making.
- Finally, the Sloan School professor confronted with inventory oscillations at General Electric — who 60 years ago brought together all of these insights, attitudes, and experiences to formulate system dynamics and to describe it on the pages of *Industrial Dynamics*.

Summary and close

Four points serve to summarize this paper. First, the immediate antecedents of *Industrial Dynamics* are the GE case but also Drucker's critique of modelling and five years of work by Forrester and his team. Second, contemporary reaction to the book indicates that viewers saw it as innovative and significant. Third, in terms of neighboring disciplines, the book has a complex and still somewhat wary relationship with MS/OR, it advanced system science, but cannot be said to have taken the social sciences by storm, and it anticipated PSMs. Fourth and last, *Industrial Dynamics* supports a biographical interpretation, in that it channels many elements of Forrester's life experiences.

This is a good moment to reflect on this book. Various dates are proposed for the creation of the system dynamics field. Some relate to the early intimations of system dynamics: for example, Forrester's first *Harvard Business Review* paper is used in support of 1958, whilst his arrival at MIT's Sloan School or his writing of "D-memo zero" both generate 1956 as a plausible candidate. However, to this author, 1961 is the most significant date. The justification is the appearance of *Industrial Dynamics*. This is the capstone of the earlier pieces. With it, Forrester wove together his knowledge, his accomplishments, and his personal experiences. With it, Forrester produced a clear statement of the whys, wheres, and hows of the discipline of system dynamics modelling, along with the most detailed announcement of his ambitions for the field. With it, Forrester generated some of the most noteworthy reactions from contemporaries. Its lessons are still being teased out (Richardson, 2022) and it rewards repeated study

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by anyone serious about the field. The anniversary of its publication merits acknowledgement.

What of the future? As an example of enduringly significant work, Platt (1964) used Galileo Galilei. Yet *Siderius Nuncius* is not on the syllabus for physics students. Newton's writings are not themselves on the syllabus for mathematics students. Economics students sometimes dip into Adam Smith and Keynes—though these are younger works. These authors' work made founding contributions to their fields but today people use other texts to learn these ideas. Where does that leave *Industrial Dynamics*? It is a reasonable expectation that one day it too will not be on the syllabus. However, that will not be for a while yet. That is because it is more than the founding work of the field. It is still the source and origin of its aspirations, general approach and many of its specific elements. As that *fons et origo* it will be read for a while yet.

There is a related but broader comment. In his review, Wagner suspected that the system dynamics approach was such a combination of "ingenuity … art, mystique, and persuasion" that it could only be used by "the master and his disciples" (Wagner, 1963, p. 186). That "master" certainly travelled a long way in space and time and thought during his long life, and his work bears the hallmarks of his unique, personal experiences. Nevertheless, with *Industrial Dynamics*, Forrester opened up a route for many to study and use the approach — and to develop it further. Perhaps the best response to Wagner's challenge can only really come from the record of the last 60 years — and from what the community of system dynamists does in the future with the ideas to be found on the pages of *Industrial Dynamics*.

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Notes

[1]These key elements can be cast in various different ways. This is something that Forrester himself did: Forrester (1960/1975) gives four, whereas Forrester (1964) points to five. The three here are closest to a version given in Forrester (1973).

[2]The 14 "obvious truths" do not appear as such in *Industrial Dynamics* though the underlying ideas suffuse the book. Their first appearance may be as a D-Memo (Forrester, 1960). They can easily be accessed today via that reference. However, this D-Memo — just the list of 14 by itself, not the other material in Forrester (1960/1975) — was also republished in *System Dynamics Review* (Forrester, 1960/1987).

[3]The System Dynamics Society records show a total of 154 items dated 1956–1961, items that are plausible influences on *Industrial Dynamics* (See: https://test1.systemdynamics.org/dynamics-memos/). These include pieces by the notable computing pioneer Phyllis Fox, system dynamicists Will Fey, Ed Roberts, Jack Pugh, David Packer and others, some anonymous pieces, and more pieces by Forrester himself. They contain further examples of system dynamics models, various reports concerning the development and operation of the computing language "SIMPLE" and of "DYNAMO, an IBM 704 Program for Generating Dynamic Models." There are also assignments, exams and a list of suggestions for thesis topics. There is a task of "intellectual archaeology" to be undertaken here. It would involve understanding which ideas appeared when in the D-memo series, how these might have been influenced by other contemporaneous work, which of these ideas appeared in *Industrial Dynamics*, which did not or were changed and—perhaps the hardest part—the reasons behind all this. That, however, is not the task of this paper.

[4]Platt's actual position has been stripped of context and somewhat embellished by a number of later authors. The re-cast form is that *The New York Times* DID favourably compare *Industrial Dynamics* with the seminal books of the canonical authors listed. This is not quite what Platt wrote. The original article was consulted and is accurately represented in the text, both its aspirations and its caveats. Platt was offering his informed guess that *Industrial Dynamics* was one of quite a number of books that MIGHT conceivably come to be seen in that way. Or might simply be more significant than most others around at the time.

[5]Wagner records a price of $18.

[6]Sadly, the author has yet to find any further record of this discussion.

[7]This aspiration is clear from *Industrial Dynamics* and can also be seen in a number of other early pieces, for example Forrester (1964). The position is accepted by David Allison when interviewing Forrester (Forrester, 1998) and is explicit in Forrester (1993). The system dynamics profession is compared with that of "engineering, law, and medicine" in Forrester (1980, pp. 7–8). It is clear that Forrester held to the ambition to establish system dynamics as a profession in its own right (Forrester, 2007). The comparison with medicine can also be found in that 2007 paper. Note the link between this and the quoted remark of Wagner (1963) likening Forrester to a medic. It also bears mentioning that the Drucker (1959) paper cited by Forrester itself compares the profession of medicine with management.

[8]As an additional justification for this separation it is notable that Forrester observed that those with an MS/OR training had much less success than others when trying to pick up the ideas of the new field (Forrester, 1960/1975).

[9]For example Keys (1988, 1990) suggests that system dynamics was a hard system approach when originally created and only later experienced significant — almost revolutionary — change when dealing with groups having a range of opinions. This also relates to the work of Flood and Jackson (1991) in which system dynamics is crudely categorized as based on "unitary" assumptions about organizations (contrasted with "pluralist") and "simple" assumptions about the system under study (contrasted with "complex"). In essence, these impoverished views cast the field as "an attempt to apply the ideas of control engineering to socio-economic problems" (Keys, 1988, p. 218), ignoring or being unaware of the importance attached to the personal experience of model building and the associated process of experimental learning. In fact, the working through of more "interactionist" forms of system dynamics is more accurately viewed as evolutionary, as a re-crafting and development of the field's early assumptions. Subsequent work in systems science is certainly more reflective of how system dynamics actually works with groups (Jackson, 2003, 2019). Nevertheless, a full understanding that the roots of this are to be found in *Industrial Dynamics* still seems lacking.

[10]This is not to suggest that *Industrial Dynamics* is not heavily influenced by the time in which it was written. Chief of these influences are its optimism and its view that it is technology and scientific rationalism that can play the most effective roles in improving all aspects of the human condition. This notion has been characterised by the "moon-ghetto metaphor," the roots of which lie in the comment:

> The techniques that are going to put a man on the Moon are going to be exactly the techniques that we are going to need to clean up our cities … the systems analysis that we have used in our Defence Department; the systems analysis that we have used in our space and aeronautical program — that is the approach that the modern city of America is going to need if it's going to become a liveable social institution.
> (Hoos, 1972, p. 88, quoting a 1968 speech by U.S. Vice President Hubert H. Humphrey at the Smithsonian Institution, Washington DC)

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This view has been seen by some as quaint and even naïve (Nelson, 1974; Rosenhead, 1989a) but one must admit that its presence is discernible in *Industrial Dynamics* — and that aspects of it persist today. For a specific insight into Forrester's engagement with the distinctive technophilia of those times see Malczynski (2020) and Malczynski and Lane (2023). The wide range of contemporary influences on *Industrial Dynamics* is explored in detail, and with considerable insight, by Crossett (2007).

[11]This ambivalence can be seen in the part of *Industrial Dynamics* referred to by Richardson. The key step—identify a problem—might also be part of a process to model an actual system in a realist manner, the identified problem serving merely to consider its boundary, to help decide which aspects of reality needs must be included in a model. Additionally, the list of steps goes on to express more realist tendencies; it refers to "the real system" and—three times—to "the actual system" (Forrester, 1961b, p. 13). In fairness, Richardson admits that regarding this point "the evidence is scant," and that he may be applying his own bias (Richardson, 2022). The same can be said of this paper.

[12]Figure 4 image credits:

Top (both)—Images scanned by Forrester from prints in his personal collection, captions from personal emails from JWF to DCL that accompanied the scans.

Bottom left—Courtesy National Archives, photo no. 80-G-35657, public domain.

Bottom right—Picture used with the permission of The MITRE Corporation. Copyright © The MITRE Corporation. All Rights Reserved.

[13]The original was said of Pasteur but concerns an experiment by Oersted:

> Sur sa table se trouvait une aiguille aimantée, placée sur son pivot, et il vit tout à coup (par hasard, direz-vous peut-être, mais souvenez vous que, dans les champs de l'observation, le hasard ne favorise que les esprits préparés), il vit tout à coup l'aiguille se movoir et prendre une position très différente de celle que lui assigne le magnétisme terrestre. [On his table was a magnetic needle, placed on his pivot, and he suddenly saw (by chance, you might say, but remember that, in the fields of observation, chance favours only the prepared spirits), he suddenly saw the needle move and take a position very different from that assigned to it by terrestrial magnetism.]
> (Vallery-Radot, 1911, p. 88)

[14]Figure 5 image credits:

Left—Courtesy of Institute Archives and Special Collections, MIT Libraries, Cambridge, MA, USA. Full source details are: Jay W. Forrester Notebook #47, November 3, 1948—September 24, 1950. MIT, Magnetic Core Memory records, AC-0337, box 98. MIT, Institute Archives and Special Collections.

Right (both)—Reprinted with permission, Courtesy of MIT Lincoln Laboratory, Lexington, Massachusetts.

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[Correction added on 20 October 2022, after first online publication: Reference details of 'Malczynski and Lane (2023)' and 'Rand (2003)' have been updated in this version.]

APPENDIX: FROM "INDUSTRIAL DYNAMICS" TO "ANY OLD SYSTEM DYNAMICS"?

The actual detail of how the name of the field was changed appears quite subtle. The process is ruefully summarised as:

> System dynamics, we should remember, started out as "industrial dynamics." Then we had "R&D dynamics," "urban dynamics" and "world dynamics," and finally just "any old system" dynamics. (Richardson, 1996, p. 1).

Interviews with those there at the time will surely play a role in getting to the bottom of the change. Nevertheless, the written record provides some interesting and useful insights.

Given the General Electric experience that initiated 'industrial dynamics,' it is easy to see why it was initially given that moniker. A D-memo on the definition of the field states that it applies to "a company, an industry, or a national economy" (Forrester, 1961a, p. 1). However, the applications of the approach quite quickly spread to non-industrial ones. By the time of publication of a collection of exercises on the technique, it was being applied to problems as diverse as the "dynamics of corruption in government" and "air force logistics" (Jarmain, 1963). Although these and the other examples can be found in earlier D-memos, this collection is arguably more significant

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because it was published—and therefore constituted a public statement about the scope of the field.

An early mention of the term "system dynamics" can be seen in Forrester (1967). Here he is referring to outside work (by Bell Laboratories), work concerning motion in physical systems. The memo is still addressed to "Industrial Dynamics Staff."

However, a certain discomfort, perhaps even disquiet, can be detected in Forrester's subsequent, externally published writings. A paper presented in early 1967 but published in late 1968 does not apply any label to the approach being used (Forrester, 1968c). Earlier in 1968 he is clearly using "industrial dynamics" but uses "system dynamics" four times to describe aspects of his project, using the term to mean "the dynamics of the system" (Forrester, 1968b). There is no such prevarication in Forrester (1968a), as may be seen from its title. In *Urban Dynamics* he states that he is using the "industrial dynamics" method but immediately adds that the term, "has become too restrictive because the methods are applicable in many fields other than industrial management" (Forrester, 1969, p. 1).

The position of *World Dynamics* takes this insight to a logical conclusion:

> the name [industrial dynamics] has become a misnomer now that applications are becoming important outside the industrial corporation. Because the methods apply to complex systems wherever we find them, a better name is "system dynamics." (Forrester, 1971b, p. 13).

This trajectory is confirmed by the available internal documentation—and potentially narrows down the timing. A memo dated only as "Spring 1970" gives a reading list for the "Industrial Dynamics Course" (Anon, 1970a) and the term is certainly still used in materials in April, June, and August. However, during 1970 there is something of an interregnum regarding the name of the group doing this work. Some D-memos refer to an "Urban Dynamics Group" (see Richardson quote above), or the "Feedback Dynamics Laboratory," whilst some have no explicit attribution. Of course, in this period Forrester was working extensively for his meeting in Boston with Club of Rome representatives, work that would lead to *World Dynamics*.

By October 7 of that year Forrester was ready to make a change and do so very publicly, in a hearing at the U.S. Congress:

> I am speaking of what was earlier called "industrial dynamics." The name was a misnomer because the methods apply to complex systems regardless of the field in which they are located. A more appropriate name is system dynamics. (Forrester, 1970d, p. 2)

What may be the first appearance of "System Dynamics Group" then occurred on November 5th (Anon, 1970b). The next day Forrester

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introduced the methodology that he was using with the Club of Rome and now called it "The field of System Dynamics" (1970a, p. 1). In Forrester (1970c), dated November 16th and labelled "Urban Dynamics Series," we see what may be Forrester's first explicit reference to the "System Dynamics Group."

There seem to have been some implementation delays, since throughout October and November there are memos referring to "Dynamics Group" or "Dynamics Staff." There are even late holdouts for "Industrial Dynamics" on November 9th and 25th (respectively Pugh, 1970; Henize, 1970). However, by December 7th Forrester was speaking of "the concepts and methods of System Dynamics (formerly 'Industrial Dynamics')" (Forrester, 1970b, p. 1) and memos referred to the "System Dynamics Group." The change was complete.

There is a surprising factor which makes this note relevant to the present paper. It is that the term "system dynamics" is used in *Industrial Dynamics*. However, perhaps one should not be too surprised; in the majority of cases it is used not as a label but rather as a descriptor, clearly meaning (and sometime directly substitutable with) "the dynamics of the system" or "the dynamics of systems." The closest one gets to its use as a label is "a system dynamics study" (p. 128) — but still the ambiguity lingers. The fact that the term is used 21 times in the book is an interesting indication of familiarity on Forrester's part. Perhaps this helped lay the ground for the later formal shift in name for the field.

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