Management System Dynamics

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For

Julie, Jonathan, and Robert

Preface

All organizations – business firms, cities or economic systems – are liable to be diverted from their chosen paths of growth or stable operation by the shocks which fall on them from the outside world, or by pressures generated within the organization. The 'shock' may be an opportunity, such as a firm attempting to react to an enlarged market, or it may be unpleasant, as when changes in international market prices affect the balance of trade. The shocks may be unexpected, foreseen, or self-inflicted, but the essential problem for managers is that of controlling the organization so as to take advantage of favourable opportunities while defending it against unpleasant upsets.

This book covers the principles and techniques for applying control concepts to business and economic problems. The subject is called 'System Dynamics' or 'Industrial Dynamics'. It owes a good deal to Control Theory, and other disciplines, but has important differences from them. System Dynamics is an extension of the existing area of Management Science. It addresses problems of controllability and integrated policy design, but it is not an optimizing approach, nor does it cope with the stochastic processes of queues and decision theory.

The book is intended for practising management scientists, corporate planners and economists who wish to know what System Dynamics is about, and if and how to use it in practice. It should also be useful to students of management, management science, economics, and other disciplines who require training in dealing with problems of controllability and policy design. Carefully used, i.e. without Chapter 4 to 8, it should benefit those students of management and administration who require the broader view of policy-making and its effects.

The economics of book publishing have prevented the inclusion of some non-essential material which it would have been useful to have covered. In particular the number of case studies has had to be restricted and those which are included are drawn from the business firm. It is hoped that readers who are interested in other areas will be able to visualize the applications, perhaps with the aid of the bibliography in Appendix C. The techniques which have been treated should, however, be sufficient to carry the practitioner through most of the problems he is likely to meet in the real world.

The material has been arranged so that the reader can study only those parts of the text which relate to his needs without losing the thread of the argument. New ideas are brought in carefully as they are needed, and the reader who invests the necessary effort should be able to follow it all.

The principal requirements for successful work in System Dynamics is understanding of the way in which the organization actually works, rather than advanced mathematical skill. For this reason the techniques described here are mathematically rather simple, so they should be easily learned by readers who have not had training in the mathematics of control systems.

The student who lacks practical experience may be led to think that, because the techniques are comparatively simple, so are the problems. This is not the case. The experienced management scientist will recognize that we are dealing with problems which come near to the very heart of the managerial task.

The application of System Dynamics is not limited to the type of problem described in the case studies. A careful reading of Chapters 1, 9 and 13 will suggest how to identify problems suitable for dynamic analysis.

Professor J. W. Forrester of the Massachusetts Institute of Technology was the originator of System Dynamics. I am grateful to him for initiating me into System Dynamics and for sparking my own interest by his powerful intellect. Dr. Carl Swanson, lately of MIT, influenced my early work in System Dynamics by his own enthusiasm and patient help.

My colleagues Dr. John Sharp and Ajita Ratnatunga have been an enormous source of help and criticism both in the writing of this book and in building up the Bradford System Dynamics Group. I am deeply grateful to them, and to the students who have tested the material in teaching. Mrs. Margaret Swift, Christine Packer and Brenda Akers typed the manuscript from my horrible handwriting and, in particular, Mrs. Akers bore the brunt of completing it under pressure, and the tedium of its revision.

Hints on Using the Book

The book has been written so as to be flexible in use for teaching or private reading. Experience of using it as a teaching vehicle suggests several alternatives:

1. For a quick general view of the nature and applicability of system dynamics read chapters 1, 9 and 13, glancing at Chapter 10 to 12.
2. A first course in the techniques can be based on Chapters 1 to 8 supplemented by careful use of parts of Appendix B for more examples of equation formulation.
3. The practical application can be studied via Chapters 9 to 13 simply reading the case studies but not running the models in Appendix B.
4. To improve the student's facility in dealing with complex models Chapters 10 and 11, and Appendix B.10 and B.11 can be used to set up and run models for student experimentation.
5. A course in corporate modelling, to link with a Business Policy course, can be based on Chapters 9 and 12. The model of Chapter 12 can be used to allow the student to experiment with policies with either the instructor or the student carrying out the model runs as appropriate.

The programs in Appendix B are given in full to provide either many examples of equation formulation (which is the greatest hurdle encountered by the student of mathematical modelling), or vehicles for model handling and experimentation depending on available time and achieved skill. There is a lot of material in the book and the reader should not attempt to digest it all within a term. Ideally it should become a work to which he refers from time to time as the need arises.

Suitable problems with solutions, and further case material will be found in R. G. Coyle and J. A. Sharp, *Problems and Cases in System Dynamics* which has been prepared as a companion to this book.

How to Read the Computer Graphs

The book contains a large number of graphs illustrating system behaviour. The graphs were produced directly on the CALCOMP Plotter of Bradford's ICL

Computer and I am grateful to Mr. A. K. Ratnatunga for developing the software to do this. It is, however, necessary to understand how the graphs are interpreted and the reader should make sure he is clear about this before trying to make sense of the system performance shown by the graphs.

Each graph contains the dynamics of one or more system variables on a horizontal scale of time. Time is measured in weeks or months as appropriate to the system, and this time unit is printed under the horizontal scale.

Each variable has its own line pattern, for example, a solid line or one of several variations on chain dotted or dashed lines. The same pattern is used to draw the vertical scale for that variable and is continued below the vertical scale and then to the right until it points to the variable name and definition which appears under the time axis. For example, in Fig. 2.19 Production Ordering Rate is shown by a solid line which is the first scale encountered as one reads to the left. The solid line is then carried down in an 'L' shape until it points to the variable name ORATE and then the text definition of this is the Production Ordering Rate, measured in units per week. Similarly, Inventory has the variable name INV and is plotted as a chain dotted line which appears as the lowest of the curves, and at the extreme left hand of the scales. The first three variables in Fig. 2.19 are plotted to a common scale so that the three patterns representing them are drawn close together with common numbering on the vertical axis.

This CALCOMP Package is a standard feature of the DYSMAP language described in Chapter 4 and has flexible options for common or individual scaling as appropriate to the problem.

Contents

Chapter 1

Introduction to System Dynamics

1.1 The Basic Problem

All business firms, economies and social organizations show DYNAMIC BEHAVIOUR. That is, as time passes, the variables by which we measure their condition (such as sales, profits, stocks, balance of payment, unemployment, and many others), fluctuate noticeably, sometimes alarmingly as when cash reserves fall, and sometimes, of course, gratifyingly such as when profits rise. Inhibiting the undesirable variations, and/or promoting the beneficial ones, are objectives for the managers concerned, and this book describes the analysis of such problems. First we show, by an example, that there is a problem to analyse.

A firm holds an inventory of finished goods, which is depleted by sales and replenished by production. Such inventories rise and fall, frequently by serious amounts. It might be argued that these variations are simply due to external fluctuations in sales. The subject of System Dynamics exists because this supposition is not necessarily correct.

Let INV.START and INV.END be the inventory at the beginning and end of a time period, a week perhaps. Let PROD denote the amount manufactured in the period and SALES the quantity sold, then

INV.END = INV.START + PROD – SALES

Now:

1. The variation in SALES from one period to the next certainly are at least a partial cause of the observed variations in inventory.
2. PROD is subject to random variations due to machine breakdown, material variations, etc., but these are usually comparatively minor and do not help very much in explaining the behaviour of inventory.

   These points are fairly obvious, the next is the important factor

3. PROD usually varies because management choose to alter it. For example, if inventory falls too low management may decide to increase production to compensate.

Clearly, MANAGERIAL POLICIES AFFECT DYNAMIC BEHAVIOUR and dynamic behaviour results from the way in which external variations, such as in SALES, are responded to by management. The policies, or rules by which these responses are selected, may diminish the effect which the external shock has on the firm or they may, of course, make matters worse. It often happens that a policy in one part of the firm conflicts with one in another part in such a way that neither policy is effective.

The essential aim of a System Dynamics study is to find policies which will control the firm effectively in the face of the shocks which will fall upon it from the outside world, which will not make things worse than they need to be, and which will be properly attuned to one another.

We can therefore say that System Dynamics is: *A method of analysing problems in which time is an important factor, and which involve the study of how a system can be defended against, or made to benefit from, the shocks which fall upon it from the outside world.* Alternatively: *System Dynamics is that branch of control theory which deals with socio-economic systems, and that branch of Management Science which deals with problems of controlability.*

In a practical situation there as so many complexities that the common sense approach is insufficient, and likely to be misleading, and a formal discipline is needed. It is with such a discipline, and its techniques, that this book is concerned.

This example was about inventory. It could equally well have been labour force, production capacity, cash reserves, balance of payments, unemployment, housing stock, or many other variables, and the organization could have been the economy, a city or region, an ecology, rather than a business firm. The reader should try to envisage these, and any others he can think of. In each case he should list the factors which affect the variable and think about why these factors vary and, in particular, the extent to which the variation is due to chance, or on the other hand, to 'policy'. This exercise should illustrate the widespread nature of this kind of policy-influenced variation.

In some cases, such as an ecology, there is little or no conscious choice as there was for the inventory case. For these 'unmanaged' situations variables such as the birth rate of a species of fish change because of response to, say, food supply. There is still variation, however, and we may simply wish to understand it better by explaining how it comes about, or we may be interested in how man might effectively interfere by, say, a fishing control policy which would give good yields without annihilating the species.

In most cases the reader will notice there is a kind of structure. For example, a company which sells from stock usually takes the stock level into account when planning future production. If inventory is too high, production will usually be cut back to some extent and vice-versa. This creates a loop, in which inventory affects production which affects inventory which, in turn, influences production again, and so on. System Dynamics is concerned with detecting these loops and, by analysing them, improving performance. Usually there are many loops, some of them very complicated, and we need special tools for the analysis.

1.2 Fundamental System Concepts

There are many definitions of 'system', a convenient one being *a system is a collection of parts organized for a purpose.*

The parts may be something recognizable, such as a cash balance, a stock of product, or a factory – the size depending a great deal on the point of view and the level of detail required. However, the parts also include the decision rules or policies by which the system is controlled, and the information linkages within the system. It is easy to recognize the functional parts and it has to be stressed that policies and information paths are also parts.

The way in which the parts are connected together, or *organized*, is an important aspect of a system, and the information link parts are the major means by which organization is achieved. The minor features of organization are the physical flows of material and orders from one part to another. These usually arise from physical necessity in that the output from the production department 'part' has to go somewhere, such as into the inventory 'part'. The important effects on system performance will derive from the way in which the production department arrives at how much to produce. This will depend on whether the production department uses, say, sales forecasts *and* the state of inventory. If it does, then the department is organized with the inventory part and with the forecasting part. Furthermore, another part enters into the problem, namely the decision rule by which information from the parts with which production is organized is transformed into actions within the production function. Clearly, the overall behaviour of the system will be strongly affected by the parts themselves *and* by the manner of their organization.

All practical systems have a purpose, which is usually a strong influence on their operations. The system organization, and the collection of parts it possesses, arise from its purpose, though often in a very haphazard and vague way. It is a truism that parts eventually acquire purposes of their own, survival being one, and purpose conflicts are common and damaging.

Although definitions and their elaboration are useful, a far better understanding of the system concept, and System Dynamics as a subject, can be gained by studying systems in operation. That is what this book is about, but we shall consider two simple examples at this stage.

1.3 Illustrations of System Ideas

Consider two simple subsystems: a car suspension mechanism and a production–inventory control rule.

The first has the following obvious parts: a wheel, a spring, a shock absorber, a car and its occupants. The spring and the shock absorber physically connect, or organize, the wheel and the car. There are two other parts, the stiffness of the spring and the damping of the shock absorber, which together control the way in which the suspension will respond when the wheel is shocked by passing over a bump in the road surface. In a very real sense the stiffness and the damping 'decide' how the car body is to respond to movements of the wheel, and we can regard them as decision rules or policies for controlling system response in the face of outside shocks. These decision rules are built into the car at the choice of its designer and can only be changed with some labour and within limits.

The purpose of the system is to insulate the passengers from the road surface, and to keep the car in one piece.

As the car is driven over a country road the wheel is subjected to shocks from the road surface but, if the suspension is well designed and in good order, the passengers have a smooth ride. If, however, the designer has made a poor choice of the decision rules, the suspension will amplify the shocks and the passengers will feel them as being worse than they really are. Clearly, poor rules can make behaviour far worse than it needs to be.

The suspension has to be able to deal with minor road variations, and it also has to cope with major changes such as from the level to an uphill slope. It has no way of knowing whether a particular shock from the road is a minor bump, which it should try to smooth out as much as possible, or the start of an uphill grade which it must not ignore. Its design must be a compromise, between reacting too readily to the first of these and too sluggishly to the second.

Even a well-designed suspension will give poor performance if the driver does not operate it properly and, by driving too fast or too slowly for the road conditions, tries to make the system give performance which it is inherently incapable of providing.

Notice that we do not expect the suspension to adjust its behaviour now to allow for the road conditions ahead. Such 'forecasting' would be impossible, so the suspension is designed to give good performance whatever the shocks it meets. Naturally, the driver 'forecasts' and, by controlling his speed, attempts to regulate the shocks, but this is a very uncertain process which is much affected by visibility, the driver's experience and his desire for speed. The suspension thus has to be designed to cope with his mistakes and the designer does not rely on the driver being able to make perfect forecasts. The success of this design process can be judged by the generally excellent performance of popular cars in a wide variety of road conditions and an even greater variation of driver skills.

The contrasting production–inventory system has, as parts, an inventory, a manufacturing delay dictated by technical factors, a production start rate and a production completion rate. Its decision rule part determines the production start rate. There are many possible information stream parts which could feed the decision rule and the designer's problem is to choose which ones to use, and how to transform their content into a production choice.

The purpose of the system is usually to maintain inventory at a satisfactory level whilst keeping production fairly stable in the face of shocks from the outside world. These shocks are variations in the rate at which inventory is depleted by customers' orders. As before, however, the design has to be a compromise between the need to smooth out noise and to respond rapidly and smoothly to major changes.

The similarity between this and the suspension system is very marked and they can be described by the same differential equation.

The designer of the production system has many more options open to him than the designer of the suspension system, but his problem is very similar, namely how to make his system controllable in the face of external shocks. Attempts may be made to forecast consumption, though there will be error, as in the case of the driver attempting to predict road conditions around the next bend. The production system, therefore, has to be designed to cope with shocks and errors and to give a good, controlled response under a wide range of conditions.

The wide range of options available to the industrial system designer complicates his problem. The car designer only has springs available to him and simply has to choose the right stiffness. The industrial system designer has many alternatives which can be used in combination and, for each one, many more factors to play with than just the spring stiffness. Furthermore he usually has to look much more widely and consider the interactions of finance, marketing, research and development (R and D), capacity acquisition etc.

To reiterate, System Dynamics is that part of management science which deals with the controllability of managed systems over time, usually in the face of external shocks.

1.4 Models of Systems

The subject of what a model is, and what it can be used for, is a large one in management science, economics, engineering, and other disciplines. Like 'system', the word 'model' is much overused.

Basically, a model is simply a means by which we attempt to represent some aspect of the external world, in order to be able to influence, control or understand it more effectively. There are, however, various types of model, the distinction between which is by no means as clear-cut as we shall make it.

For the scale models used to plan machine layout, the nature of the modelling process is apparent. The scaled-down version looks like the real thing and the nature, purpose, and consequences of the model are readily understood. This is because making even a rough scale model of a piece of machinery can be thought of as using a 'language' which gives a good, clear, description of the real problem and which is easily understood by some person other than the modeller.

Alternatively, a model might be an intuitive mental understanding of human behaviour, as we have experienced it, which we employ in order to persuade some group of people to follow a particular course of action. A teacher unconsciously employs such a 'model' while he is lecturing, so that he may so choose his words and illustrations as to enhance his chances of conveying his meaning to his students.

This case is vastly different from the first, scale-model, example. There is no really clear 'language' by which the second type of model can be described, partly because concepts such as rapport, comprehension etc. are practically impossible to define and analyse, let alone convey to someone else, such as a trainee treacher.

We shall, in this book, reserve the term model, for a sort of half-way-house between these two extremes. In our usage we shall mean by 'model': *any formal description, in words, diagrams and/or mathematical equations, of the structure and workings of a system, together with unambiguous, acceptable, definitions of its parts.*

The three alternatives of verbal, diagrammatic and mathematical form *must* be exactly equivalent to one another, in order to be able to build an adequate model of a system. Any one form should merely serve as an aid to understanding for someone who is not fluent in the other languages.

This definition of a model implies that it may well be downright misleading to seek to analyse such intuitive processes as the dynamics of interpersonal relationships, using the methods described later in this book for analysing comparatively simple socio-economic processes, such as the dynamics of a firm, an industry, or an economy. To do so would be to attempt to impress formalism and structure on something which, by its very nature, is fluid and evolving. It must, in short, be very firmly pointed out that it is simply not the case that a formal model is always better than intuitive understanding because many of our mental processes cannot be described in words without so distorting and simplifying them as to remove most of the meaning from them.

1.5 Examples of Dynamic Behaviour

Having said that dynamic behaviour is virtually universal in systems, we now examine some cases of such behaviour. The examples are from four levels: the economy as a whole, industries within the economy, and behaviour of and within a firm. The purpose of the examples is to illustrate the following points about the dynamic behaviour of systems.

1. Dynamic systems occur very widely indeed, and at all levels of complexity and scale.
2. Systems in totally different areas often have surprisingly similar behaviour patterns.
3. In order to improve a system's behaviour (if it is bad, and not all systems are) we usually start by trying to understand why it behaves as it does. This involves trying to discover its working processes and seeing whether the knowledge, or ideas, we have about how the system operates can be supported by examining its dynamic behaviour. In this way we link together statistical data on the system's dynamics, with our comprehension of the inner working of the system. This is particularly illustrated in Section 1.7.
4. The dynamics of the system as a whole raise a wide range of problems, for its parts may well start to operate in conflict.

The examples have been chosen to illustrate points of general applicability, and the reader who is interested in business problems is urged not to omit the other sections.