

LOOP ANALYSIS AND MODEL VALIDATION

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ABSTRACT

This paper is concerned with the use of "Loop Analysis" in the evaluation and validation of System Dynamics model. The part that loop analysis plays in the overall validation process is described, and it is shown, by reference to the analysis of a complex model, how the model's behaviour may be investigated. The analysis proceeds by identifying some of the elements of system behaviour such as damping, phase-shifts and gain/delay factors, and, in the process, highlights those feedback loops that are pseudo-positive and/or unconformable. In addition to the validation aspect of the use of loop analysis, there is a valuable contribution towards the knowledge and insight of the model-builder, enabling him better to identify areas of the system which may benefit from re-design.

1. INTRODUCTION

The construction of any size or type of model leads to the inevitable problem of validation. Certain models, by virtue of their mode of construction or, perhaps, because of the simplicity of the system they attempt to represent, can be validated purely by comparing their performance against the performance of the real system. This process may be termed "external" validation, as it is assumed that the model's internal structure is sound. However, there exists a class of models which are, of necessity, based on complex systems (and are themselves complex) comprising many inter-related factors, such that they (the models) are constructed by analysing subsections of the systems and piecing together the resulting (feedback) mechanisms therefore identified. Such models are, often, large and, invariably, difficult to validate. System Dynamics models fall into this class, and so require a certain amount of "internal" validation.

At the very simplest level internal validation means checking to see that the correct answer is produced by the correct method. A "black box" producing "correct answers" from historical data may well be unable to produce equally correct

answers from real-time data. Worse still, even the model-builder will have diminished confidence in his model's performance.

The basic aspect of internal validation is that of ensuring that every equation has a logical basis, correct parameters and is correctly written. As the model evolves, this type of validation should be constantly in the model-builder's mind, and amounts to a form of "process control". At a higher level, internal validation involves the analysis of feedback mechanisms, in detail or in aggregate. This "loop analysis" provides a number of indications of how the model will behave, and so "expected" behaviour can be compared with the actual behaviour (resulting from runs of the model). Any variance of actual from expected, even though not necessarily incorrect, indicates that certain parts of the model may need to be examined further.

In addition to the use of loop analysis as a means of obtaining a benchmark for comparison purposes, there are other benefits to be obtained. By identifying the various factors leading to damping, phase shifts and gain/delay, as well as those feedback loops which are pseudo-positive and/or unconformable, the model-builder is in a better position to consider the undesirable aspects of the model's (or the system's) behaviour. With such knowledge of the structure of the model he is better able to re-design parts of it, and so encourage the desirable forms of behaviour, and suppress the undesirable. (The identification of possibly sensitive parameters also enables sensitivity testing to be carried out in a finite number of trials).

Loop analysis, then, is an important and very useful part of the modelling process, for certain types of models. The remainder of this paper concentrates on the use of an example to illustrate the method and usefulness of loop analysis. System re-design, which is not discussed here, is considered in detail by Coyle (1977).

2. THE MODEL

The model used here as a subject for loop analysis is based on the supply of, and demand for, shipping tonnage in the world market, excluding liner tonnage which does not operate in a freely competitive market place. The overall structure of the model is illustrated in Figure 1, which shows that there are two fundamental types of shipping involved — dry cargo vessels and tankers. The basic mechanism at work is such that, for each of these vessel types, the interaction of supply and demand affects the freight rates in the market (the price payable for hiring a vessel — really the price per unit of carrying-capacity) and, because of this, certain decisions are made which, in turn, affect the short-term or long-term supply. Various cycles are therefore completed and there are further pressures on the freight rates. This simple description — albeit adequate for its present purpose — belies the complexity of the system, and the model. The number of feedback loops is very large, and complications arise with the existence of variable delays in some of these loops — for example, the expiry rate of period charters (hire for a period of time, as opposed to a single voyage) depends upon the average length of such period charters, and this average length varies with freight market conditions. Not despite the complexity, but rather because of it, an attempt should be made to analyse the model before running it with data.

Before investigating any of the feedback loops in detail it is useful to consider the model structure as shown in Figure 1. Here sectors of the model form the loop elements. There are negative feedback loops based on the following sectors:

Orders/Deliveries
Scrapping
Lay-Up
Trade Change
Voyage Chartering

A positive loop centres on the Period Chartering sector, and since the freight market system exists for the resulation of

shipping supply to meet demand — a goal-seeking, negative feedback system — this positive loop is “unconformable” and may well be a fundamental cause of the large fluctuations observed in the system’s state variables. The negative loops based on scrapping and lay-up act as release mechanisms for excess tonnage when the freight market is depressed. The tradechange loop tends to negate the effects of freight rate rises in one of the markets by channelling shipping capacity into that market, and subsequently producing a negative influence on the rising freight rate. The availability of vessels capable of switching markets could therefore play a large part in the damping of freight rate fluctuations. The negative loop based on the order/deliveries sector has a goal-seeking role in that it allows orders to be reduced when supply is becoming too large. The response rates of this loop and the other loops are not identifiable at this level of aggregation and such information must come from a more detailed loop analysis.

One further point which may be made here is that it can be seen from the overall model structure of Figure 1 that demand for shipping capacity is injected into the model not at the point of ordering but at the point of chartering. In the real system it is at the interface of chartering and demand that the freight rate formation takes place, and only indirectly — via the freight rates — does the order sector respond to demand changes. The model represents the real system and has no direct information link between demand and orders, as can be seen from Figure 1. There is an indication here that this situation may not be entirely satisfactory as a method of linking supply with demand.

At this stage of the analysis of the model it is not possible to derive any firm conclusions but these initial indications are useful in providing some guide to which factors may be important in determining model behaviour. More detailed analyses need now to be undertaken in order to obtain information on the existence of factors such as loop dominance or pseudo-positivity. The next section of the paper concen-

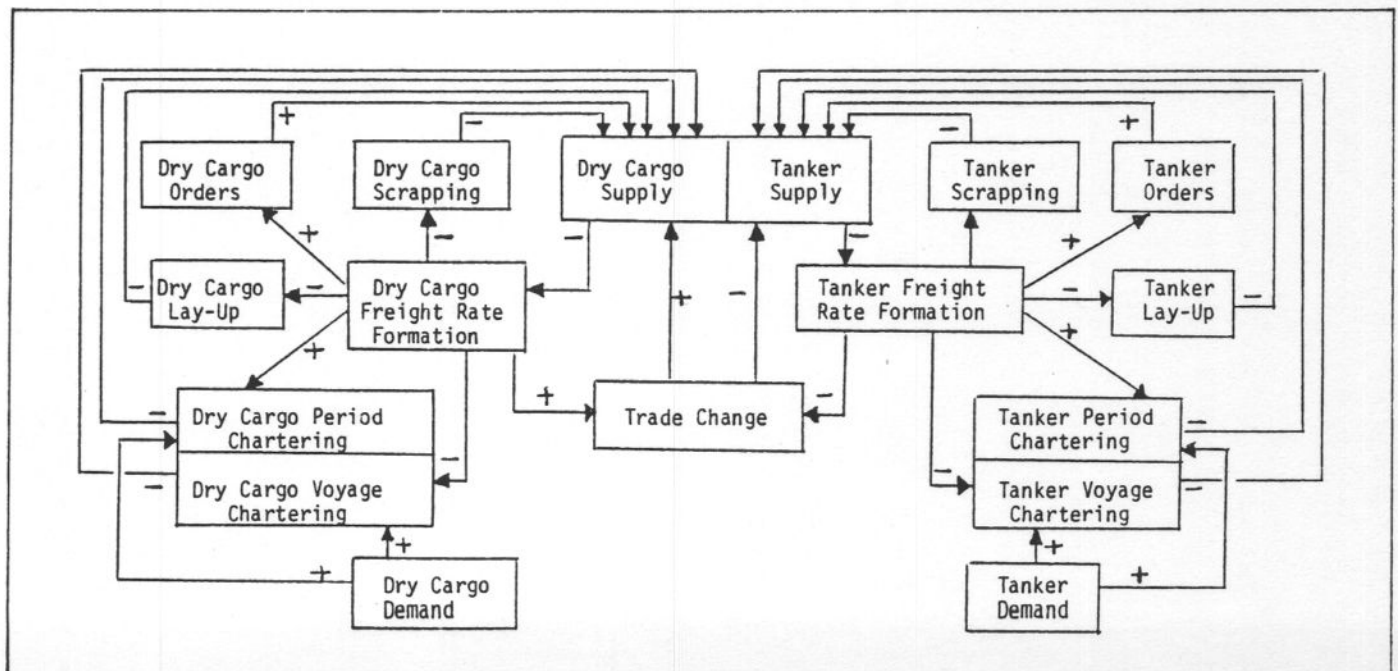


Figure 1: Schematic Diagram of a Model of the Shipping Freight Markets.

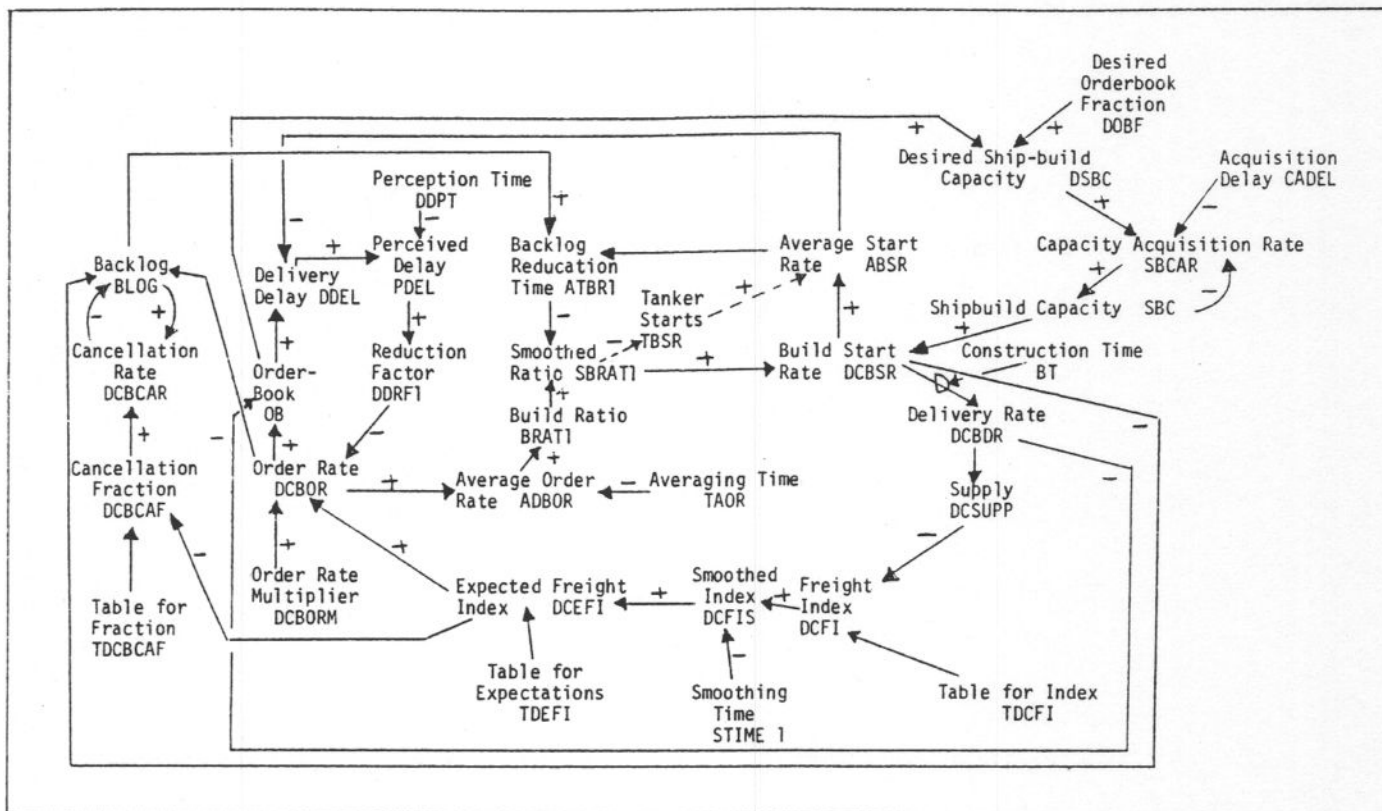


Figure 2: Simplified influence Diagram of the Dry Cargo Part of the Orders/Deliveries Sector

described loop by loop. Further, the behaviour-characteristics of each loop can be identified and thus the expected behaviour of the overall sector.

3. LOOP ANALYSIS

3.1. One Sector in Detail:

Figure 2 shows a simplified influence diagram of the orders/deliveries sector, for dry cargo tonnage. For clarity, many of the finer modelling details of this sector have been omitted, and it can be assumed that tanker tonnage exhibits similar relationships. The relationships of Figure 2 may be summarised as follows:

- * An increase in the Expected Freight Index (i.e. freight rate index) induces a rise in the order rate, which, in turn, increased the Backlog of orders and the Orderbook (Backlog and work-in-progress).
- * A rising Orderbook increases the Shipbuild Capacity (after some delay), which thereby increases the rate at which new vessels are started.
- * An increasing Build Start Rate leads to an increasing Build Delivery Rate (after a delay) and hence to a higher level of Supply. This larger supply of shipping decreases the freight index expectations, and hence the Order Rate.

- * An increasing Backlog of orders lengthens the time for which a particular order has to wait before it reaches the head of the backlog. The mix of start rates for dry cargo and tanker tonnage depends upon their relative order rates some time previously – and so this mix of orders filters through the backlog over a variable time.
- * The Backlog of orders is decreased by cancellations as the freight index expectations decrease.
- * An increasing Orderbook increases the delivery delay and discourages further orders from being placed.

There are eleven separate feedback loops in Figure 2, and these are shown individually in Figure 3. For each of these loops are identified the polarities, the delays, the total delay, the orders of the delays, the numbers of pure integrations and the gain factors. Table 1 summarises these loop elements, and from this table can be obtained the following information:-

- (i) Loops A and B have high order delays which may lead to under-damping in the system.
- (ii) The long delays of loops A and B provide a certain amount of damping which could compensate for the under damping or destabilising effect produced by the high order of the delays.

(iii) Loop A is positive and seemingly unconformable in a system which is essentially goal-seeking. Loop A is, in fact, pseudo-positive as can be seen from an examination of the effects of an increase in the gain factor DCBORM: increased dry cargo orders lead to a larger backlog which, in turn, increases the time over which new orders must wait in the queue. This time is used to smooth BRATI to produce SBRATI so that an increase in the queueing time appears to produce a decrease in SBRATI; such a decrease is not possible. In fact, this negative link (making the loop, as a whole, positive) is by-passed by the positive link in loop B between ADBOR and SBRATI. Hence loop A never acts as a positive loop. It can also be observed that the integration in loop A (at DCBLOG) would produce a phase shift which would "slow-down" the flow of information in that loop from DCBOR to SBRATI.

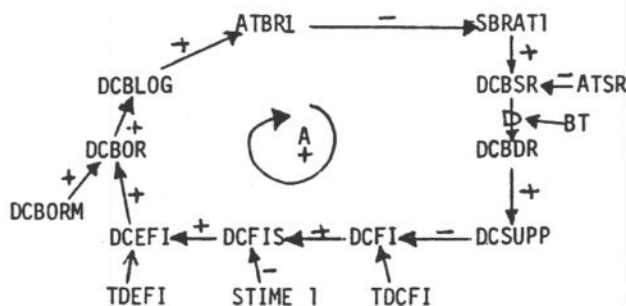
(iv) Loop C is pseudo-positive, being by-passed by the faster-reacting negative loop D. (Loop C implies that an increase in cancellations leads to a further increase in cancellations). The cancellation fraction DCBCAF acts as a gain factor in loop C (via the table function TDBCFAF) and a delay in loop D.

(v) Loop E is negative and exerts a negative influence on the order rate as the latter increases the length of the delivery delay. A short loop delay indicates a relatively fast feed-back of information.

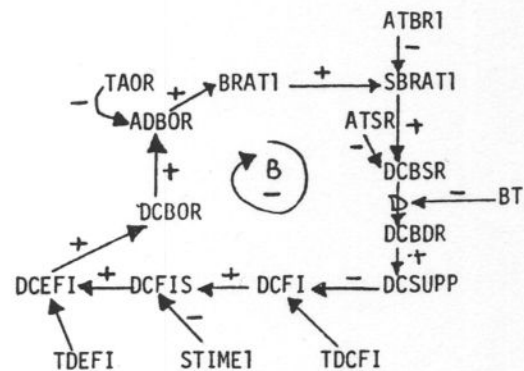
(vi) Loops F₁ and F₂ relate to the dry cargo and tanker sub-sectors respectively. An increase in start rates produces a lowering of the backlog reduction time, ATBRI, which then increases the average start rate ABSR via loop F₁ and decreases ABSR via loop F₂. These two loops, in fact, balance one another both having identical delays and gain factors.

(vii) Loops G₁ and G₂ balance one another in the same way that F₁ and F₂ balance. The variable SBRATI is used to allocate shipbuilding capacity between tanker and dry cargo tonnage so that any fluctuations in SBRATI can not possibly lead to either an increase or a decrease in the average start rate. In fact, even if G₂ did not exist the loop G₁ would never operate as it would continually be by-passed by the shorter-delay loop E.

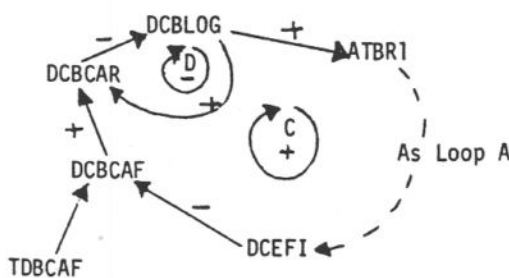
(viii) Loop H₁ is negative and operates so as to keep the shipbuilding capacity in line with the demand (as measured



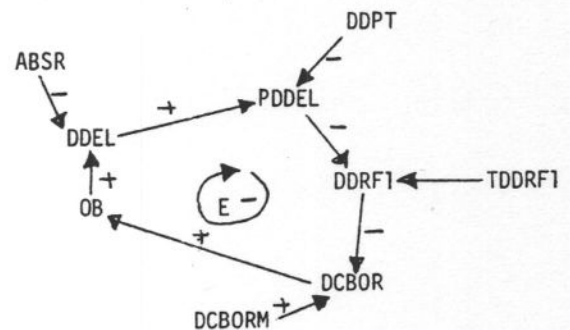
Loop A



Loop B



Loops C and D



Loop E

Figure 3: Feedback Loops in the Simplified Order/Deliveries Sector (Dry Cargo Relationships)

by the size of the orderbook). Both the delay order and the average length of the delay are high so that both attenuation and under damping influences are present. There are three pure integrations which may produce a considerable phase-shift effect for input periodicity of three years or more. Loop H_2 operates with H_1 with the purpose of reducing the rate of change of SBC as the latter moves nearer to its target, or desired, value.

The major loops in this sector are thus seen to be loops B and H_1 . Both of these loops act so as to reduce any increase in the freight index although the two loops do, in fact, have separate purposes, loop B existing for the purpose of changing the start rate in accordance with the order rate.

Points of interest in the existence and operation of these loops are:

- (a) B has the longer delay so that the effect of changes in the freight index will be felt via H_1 first. That is, a rise in order rate (DCBOR) produces — via H_2 — a rise in ship-build capacity (SBC), and start rate (DCBSR) before loop B can exert its own effect on the start rate. The variable delay in loop B indicates a variable periodicity in the fluctuations of some of the state variables.

- (b) Loop H_1 affects the start rate for both tanker and dry cargo tonnage whilst loop B and its equivalent in the tanker part of this sector, affect only their separate market areas. In terms of the overall behaviour of the system via orders and deliveries of tonnage, it appears that H_1 is the most important loop.

- (c) The single pure integration in loop B and the three pure integrations in loop H_1 can produce significant phase-shifts in these loops. Also, the delays in the loops contribute significantly to the total phase-shift for input periodicity of four years or more. The cycles of industrial production indices typically have periods of the order of five or six years and the "business cycle" is of the order of four years, so that these cycles lead to phase shifts, via the loop delays, of approximately one half of a period. The indication here, then, is that a considerable phase-shift may occur so that, for example, delivery rates and order rates may be very much out of phase.

- (d) Instability may be "injected" into the model by the several gain factors which affect both loops, as well as the factor DOBF (which regulates the desired ship-building capacity in order to retain a fixed delivery delay) acting only on loop H_1 . Any inherent instability may

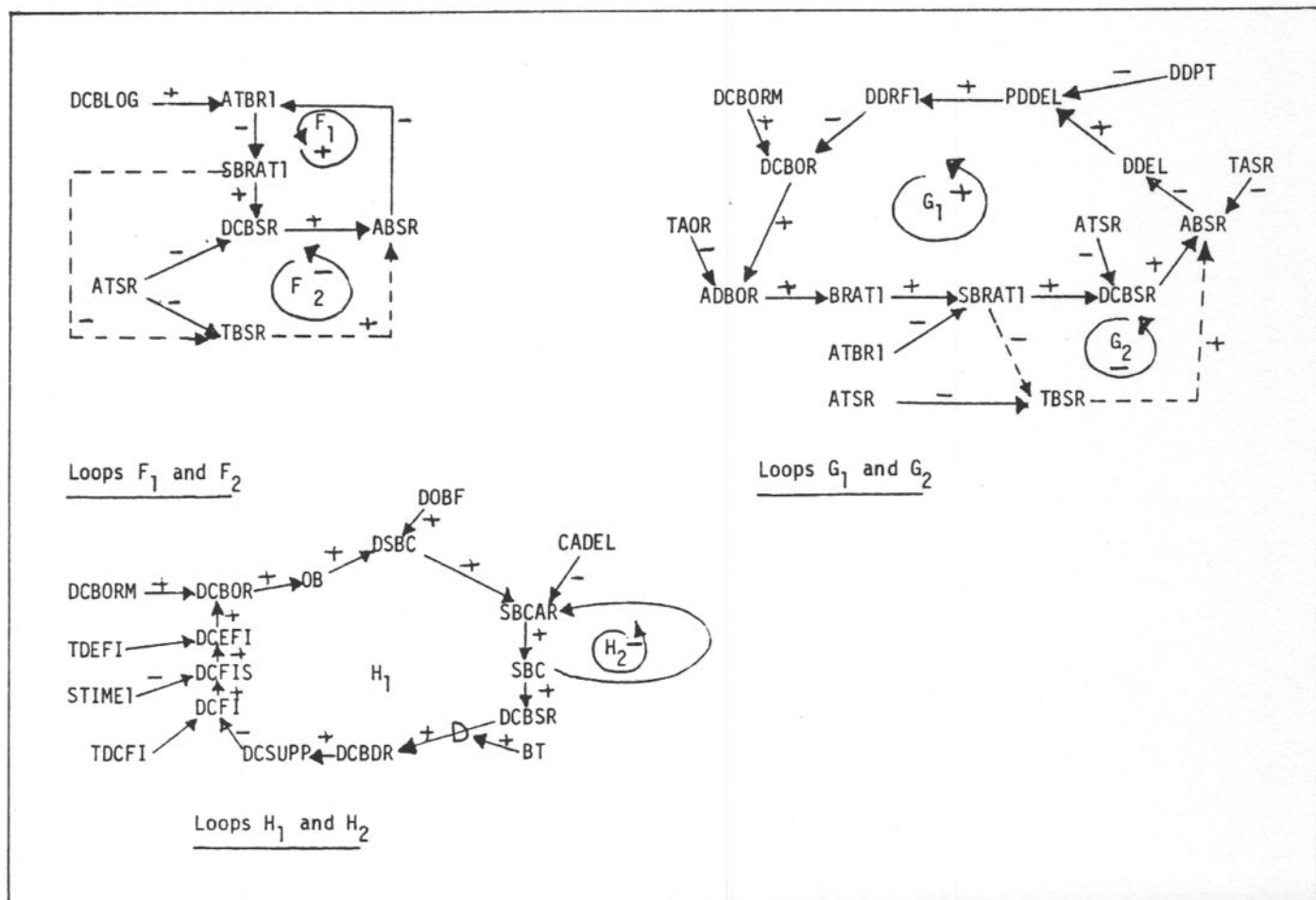


Figure 3 (cont.): Feedback Loops in the Simplified Orders/Deliveries Sector (Dry Cargo Relationships)

LOOP	TYPE	DELAYS	TOTAL DELAY (MONTHS)	ORDER	PURE INTEG-RATIONS	GAINS
A	+	BR,STIME1 ATSR	22	38	2 DCSUPP DCBLOG	DCBORM, TDCFI,TDEFI
B	-	TAOR,ATBRI*,BT,STIME1 ATSR	52*	39	1 DCSUPP	DCBORM, TDCFI,TDEFI
C	+	BT,STIME1	21	37	2 DCSUPP DCBLOG	DCBORM,TDCFI TDEFI,TDCBAF
D	-	1/DCBCAF*	Variable	1	1 DCBLOG	-
E	-	DDPT	1	1	1 OB	1-TDORFI DCBORM
F ₁	+	TASR,ATSR	2	2	0	DCBORM
F ₂	-	TASR,ATSR	2	2	0	DCBORM
G ₁	+	TAOR,ATBRI* DDPT,TASR,ATSR	33*	5	0	DCBORM TDORFI
G ₂	-	TAOR,ATBRI* DDPT,TASR,ATSR	33*	5	0	DCBORM TDORFI
H ₁	-	BT,STIME1 CADEL	36	38	3 DCSUPP OB,SBC	DCBORM,TDCFI TDEFI,DOBF
H ₂	-	CADEL	15	1	1 SBC	DOBF

Table 1: Loop Summary Table for the Loops of Figure 3

* Variable Delays

then be exacerbated by the under-damping resulting from the high order delays in the loops.

3.2 All Sectors in Summary

The previous section has detailed the kind of analysis that can be performed, and the way in which the results may be interpreted. To describe in such detail the other sectors of the model would serve no useful purpose here, but it may be useful to summarise the major findings from the analysis:

- (i) Detailed examination of the loops in all of the sectors confirms that the loops of Figure 1 represent the fundamental structure of the model. This demonstrates the value of obtaining an overall view of system structure by utilising a highly aggregated influence diagram.
- (ii) In the ordering process instability and underdamping can occur and orders and deliveries may easily become completely out of phase. Sources of gain arise in freight index formation, expectations, growth in shipbuilding capacity and order rates, whilst the high order delay in the feedback effects of the ordering decision leads to a low level of damping. Growth in the supply of tonnage is via this sector.
- (iii) The Laying-Up and Scrapping sectors provide negative loops which help to alleviate a buildup of excess shipping supply in times of freight rate depressions. The scrap process, however, is very slow acting in reducing the supply due to the long life of the vessels, and thus the long delay in the negative loop. In contrast to this,

the lay-up process is fast-acting, with a non-linear relationship between freight index and lay-up rate providing a means for the transfer of loop dominance from other parts of the system to the lay-up sector. This dominance-shift takes place at low freight index values.

- (iv) A large element of instability arises via the chartering process where a short-delay positive loop produces growth in freight rates and in the total tonnage on period charters. The presence of a negative loop is insufficient to counteract the short term growth due to the positive loop, as the delay in the negative loop is long and of high order. When the effects of this negative loop are felt, in the form of decreased freight rates, the positive loop then acts so as to further reduce the freight rate. This particular sector, then, has the overall effect of accentuating the peaks and troughs in freight rate fluctuations. (A very noticeable characteristic of the real system).
- (v) The system encompasses one area which acts so as to provide stability in both dry cargo and tanker markets. This is the Trade-Change Sector: the movement of shipping capacity between the two markets helps to reduce the extreme movements in the freight indexes, by increasing supply during upward freight index movements and decreasing it during downward movements. The loops comprising this sector have short delays and are of low order, so that a fast reaction can be expected from them.

4. CONCLUSIONS

The problem facing the model-builder, for the example used in

this paper, was one of credibility. How could the model be used with any degree of confidence that it represented the real system? In analysing the model three separate, but not independent, types of investigation were undertaken, covering the theoretical structure of the model (via loop analysis), the behaviour of the model to "test inputs", and the sensitivity of the model to certain parameter values. This paper has concentrated on the first of these, the analysis of feedback loops, and has attempted to illustrate its methodology and usefulness. Space does not permit a description here of the other two

types of model analysis, but it may be said that the loop analysis provided important guidance on sensitivity testing, and that the "predicted" behaviour of certain of the state variables — such as phase shifts between deliveries and orders — was identifiable in the various simulation runs.

References

Coyle, R.G., 1977 Management System Dynamics, John Wiley & Sons.