The accuracy of project cost and duration estimates in industrial R & D

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Abstract. This study of the accuracy of cost and duration estimates, both initial and intermediate, for industrial R & D projects, is based mainly on analysis of the records of 475 projects in four varying research organizations. Mean ratios of actual to estimated cost ranging from 0·97 to 1·51 are obtained, and mean ratios of actual to estimated duration from 1·39 to 3·04. The results are generally similar to those of other British and American studies, with which they are compared.

There is no evidence that the information gained as projects progress enables their future cost and duration to be estimated more accurately; at best, the accuracy of such estimates remains constant. No effect of project size on estimate accuracy is found; effects of project length on accuracy, and of time (i.e. increasing experience) on accuracy are found only in one organization each. The pattern of expenditure over time is examined, and found on average to be not far from linear, though with wide individual project variations.

When the individual project ratios are reduced by constant factors representing optimistic or pessimistic bias (derived from the mean ratios, and assumed to be characteristic of the firm), and then subjected to a log transformation to make their distribution more symmetrical, the remaining variation, which is a measure of the inaccuracy of estimation for the individual projects, is closely similar in the four organizations, and not greatly different in the organizations covered by other studies when the data are similarly treated.

INTRODUCTION

Most quantitative methods for the evaluation, selection, planning, and control of R & D projects, and for the allocation of R & D resources, require estimates to be made of the cost and duration of the projects. For some of these purposes, estimates of benefits are also required. Until recently, however, it has been difficult for a research manager to judge (except by trying them himself) how far the potential value of these methods might be diminished by inaccuracy in the estimates, or to assess the standard of estimate accuracy in his own organization, because there was very little published information about the level of accuracy attained in practice. Such information as there was related mainly to military and space projects (e.g. Marshall & Mecking (1962)), and might not apply to civil and industrial R & D, where virtually the only work providing directly relevant information was that of Mansfield & Brandenburg (1966).

The study to be described here, which covers a period of about three years, was undertaken as a contribution towards remedying this deficiency. Since it was started, significant contributions have been made by Meadows (1968), Allen & November (1969), and Thomas (1970); where possible, the results reported by these authors will be compared with those of the present study.

SOURCES OF DATA

The study is made up of five parts, of which four are very similar to each other. These four are retrospective analyses of records for fairly large numbers of projects (475 in all) which were compiled by the organizations concerned as part of their normal system of evaluation, planning, and control. Typically, these consist of initial estimates of cost and duration, an actual starting date, an actual completion date, and a statement of final cost incurred. Some projects also have intermediate estimates and cost statements made for project reviews, together with the dates of the reviews. There are no estimates of benefits. These four studies will be called RDU 1 to 4.

The fifth study is a much more detailed contemporaneous recording of expectations and events in a much smaller number of projects which were starting at about the same time as the study itself. Its purposes are rather different from those of the first four studies, but it provides data which can be used here. Initially, it covered 26 projects, but of these 3 were, in effect, never started, and 8 are still in progress, so that there are 15 which can be used for present purposes. They are drawn from 5 widely differing research organizations, and in general they are larger and longer than those in the other four studies. The predominant content of 6 is mechanical, of a further 6, electronic, and of the remaining 3, biological.

The four organizations in RDU 1 to 4 differ considerably in the purpose and content of their work, and may be briefly described as follows:

RDU 1 The results of this study have already been published (Allen & Norris, 1970). The organization concerned is the Scientific Services Department of the Central Electricity Generating Board, North Eastern Region, at Kirkstall, Leeds. The whole of the work falls into the category of process improvement, and is aimed at reducing the cost of electricity by eliminating causes of stoppage and expense in existing generation and transmission plant, and by contributing improvements to the design of new plant. The work covers a wide range of problems and disciplines, but is predominantly mechanical engineering, metallurgy, instrumentation, and control engineering. In addition to the programmed projects, there is a considerable amount of service work concerned with more immediate problems. Cost and duration estimates are made for all projects, and the 84 projects used in the study are therefore representative of the work of the laboratory.

RDU 2 The organization here is a large commercial

one, concerned (unlike RDU 1) with a wide variety of products (mainly consumer products), and therefore directing its efforts mainly to product innovation and improvement. There is some engineering work on processes, but the character of the research is predominantly chemical and biological. There is probably less service work than in RDU 1, 3 or 4. There is a significant element of fairly basic long-term work, but much of this (amounting to about 15% of total cost for all projects) is not covered by the 252 projects used in this study, because the organization does not insist on overall cost and time estimates for the more basic projects.

RDU 3 The organization here is in some respects intermediate between RDU 1 and RDU 2. It is a commercial organization in a process industry, making large quantities of relatively standardized products, mainly for sale to other industries, and therefore, although it does some work concerned with product innovations and improvements, about three-quarters of the projects are aimed at lower costs and better quality, through the improvement of processes. The work is predominantly of an engineering character, with a subsidiary chemical element, and considerable emphasis on process measurement and control. There is a large amount of service work. The 89 projects used in this study are representative of the work of the laboratory, but only 36 have initial estimates of final cost, since the organization again does not insist on these. The remainder have only estimates up to the first review date. There is not, as there is in RDU 2, any obvious difference in character between those projects with estimates of overall cost and duration and those without.

RDU 4 The data here are taken from an unpublished study by Wilkes (1971) of the planning and control system in which they originate. The organization concerned is a commercial one, making large and complex engineering products, in which many of the components and sub-systems have to meet very exacting specifications. Research is closely linked to design, and many projects arise from the design side, when available technical information is found to be inadequate for the work in hand. The research is entirely concerned with product innovation and improvement, although, since the products are capital goods, similar work by the user would be regarded as process improvement. The study covers 50 projects.

Some general information about the projects in the 5 parts of the study is summarized in Table 1. The average project costs are broadly similar in RDU 1, RDU 2, and RDU 4, though lower in RDU 3. The average durations, on the other hand, differ considerably, implying rates of expenditure per project about 4½ times as great for RDU 2 and RDU 4 as for RDU 1. RDU 1 and RDU 3, both concerned with process improvements, have broadly similar rates of expenditure. The 'detailed' projects have the largest average duration and by far the highest total cost, but they tend to be major projects in the organizations concerned, and are almost certainly not representative. The 'normal' projects in Table 1, amounting to between 50% and 68% of the total available, are those which are of most interest for present purposes, because they are believed to offer a valid comparison between estimates and outcomes; the reasons for eliminating the remainder are about to be discussed.

METHODS AND PURPOSES OF ANALYSIS

It may seem trivial and obvious to say that, for a valid comparison, estimates and outcomes must relate to the same thing. In practice, failure to check that this requirement is satisfied is a frequent cause of supposed large errors in estimation. An aircraft may have the same name and general purpose, but if in the course of development the specified range and payload are altered, we can no longer expect to have it for the same cost. Similarly, an R & D project can have the same title and general objective, but have had its content and detailed objectives charged in such a way as to make nonsense of the initial cost and duration estimates. Such changes frequently occur, and for good reasons, but it is important that they should be recognized and recorded.

In this study, the term 'normal' is used to denote those projects which, so far as could be ascertained, had been completed in accordance with the original intentions, and could therefore be used for comparing estimates with outcomes. Though the principle is clear, and the majority of projects can be classified without much doubt, there are some borderline cases in which it is difficult to distinguish between changes of content which are voluntary, and changes which are due to the inherent uncertainty of research. For example, a project may be concerned with finding a solution to a problem, six possible solutions initially being envisaged. After failure of these six, a review meeting decides to try a further three. Whether this is a normal project depends on whether the original intention (as understood by the estimator) was to seek a solution, trying all likely means, and starting with an initial list of six, or was to try the six, and, if these failed, consider the project completed.

In addition to the numbers and proportions of normal

Table 1. Summary of projects studied

Study	Total projects	Average cost (£)	Average duration (months)	Number of normal projects	Normal projects (%)	Abandoned projects (%)	Altered projects (%)
RDU 1	84	4,800	28	57	68	15	17
RDU 2	252	5,500	7	164	65	20	15
RDU 3a	89	2,000	12	45	51	8	41
RDU 3b	36	1,800	11	22	61	11	28
RDU 4	50	7,600	10	—	—	—	—
Detailed	16	25,000	34	8	50	31	19

RDU 3a contains the 36 projects in RDU 3b, which all have initial estimates of total cost, and a further 53 projects which have no initial estimates.

projects in RDU 1, RDU 2, RDU 3, and the detailed study, Table 1 gives the proportions of 'abandoned' projects and of 'altered' projects. 'Abandoned' is sufficiently self-explanatory, but 'altered' is a deliberately wide term to cover a remainder which differs from one study to another. For RDU 1 and the detailed study, it includes extended projects (content voluntarily increased) and curtailed projects (content voluntarily decreased). In RDU 2, where the organization is concerned to ensure that all projects are normal, there are no extended and curtailed projects, but instead there are projects which are withdrawn and re-formulated as new ones, and also a small number which are suspended, and may later be resumed. In RDU 3, there are projects which are withdrawn in this sense, but there are also extended and curtailed projects, and a larger proportion of suspended projects. In RDU 4, it is unfortunately not possible to classify the projects in this way, though it is known that none of them is abandoned, and it is likely that the majority of them are normal.

The data obtained in the 5 studies enable the following questions to be investigated.

1. The size of the errors with which cost and duration were estimated, and of any systematic bias in these errors.
2. The possible relationship between the size of the error and the size (i.e. cost) or length of the project.
3. The possible change in the average error of estimates over time, such as might result from a learning effect due to increasing experience of estimating in the laboratory as a whole.
4. The possible relationship between the size of the errors in review estimates and the fraction of the actual project duration which had elapsed when the estimates were made.
5. The possible existence of a consistent pattern of expenditure over the lives of projects, characteristic of a laboratory, which might be used to derive improved estimates of the final cost from the actual cost in the early stages.

To facilitate analysis, the raw project data, consisting of dates and sums of money, have been reduced to appropriate standardized forms and units. The main choices are to express all values as ratios to the initial estimates (which is the most generally used method in this field), or to express all values as ratios to the final outcomes. The initial estimate basis is the more appropriate one when the interest is in the provision and utilization of research resources, and therefore in the extent to which revised opinions and eventual outcomes diverge from initial expectations. On the other hand, the final outcome basis is the more appropriate one when the interest is in the accuracy with which the final outcome is estimated, and in whether and how, as projects progress, the review estimates tend to converge on the final outcome. As an illustration, Table 2 gives the raw data for a typical project, together with their counterparts on the two bases. The dates of the initial estimates, reviews, and final outcomes are expressed as elapsed fractions of the estimated or actual project duration, as appropriate.

Table 2. Example of project data

	Start	*Review*	*Completion*
Raw data			
Estimated cost	£3,500	£5,500	—
Estimated completion date	30.6.70	30.6.70	—
Actual cost	0	£1,500	£4,442
Date	1.11.69	30.1.70	18.6.70
Derived data, estimate basis			
Estimated cost	1·000	1·571	—
Estimated completion date	1·000	1·000	—
Actual cost	0	0.429	1·269
Date	0	0.375	0·938
Derived data, outcome basis			
Estimated cost	0·788	1·238	—
Estimated completion date	1·067	1·067	—
Actual cost	0	0·358	1·000
Date	0	0·400	1·000

No attempt has been made to adjust the cost estimates and outcomes for changes in general price levels, partly because of the problem of choosing the right basis, and partly because allowances for price changes might have been made by the estimators. This problem has been discussed at greater length by Thomas.

DIVERGENCE OF FINAL OUTCOMES FROM INITIAL ESTIMATES

Table 3 gives, for the five component studies, and for normal, abandoned, altered, and all projects, the numbers of projects in each class which provide a ratio of actual to initially estimated total cost, the means of these ratios, and their variability, as measured by their CV (co-efficient of variation, i.e. standard deviation as a

Table 3. Ratios of actual costs to estimated costs

	Normal	Abondoned	Altered	All
RDU 1				
Number of projects	57	13	14	84
Mean ratio	1·46	0·51	2·24	1·45
CV%	80	47	—	90
RDU 2				
Number of projects	162	50	36	248
Mean ratio	1·07	0·71	0·71	0·94
CV%	48	81	—	59
Area 1				
Number of projects	8	2	1	11
Mean ratio	1·22	0·98	1·16	1·17
CV%	52	71	—	50
Area 10				
Number of projects	21	12	3	36
Mean ratio	1·15	0·67	0·36	0·92
CV%	59	105	—	77
Area 12				
Number of projects	13	1	2	16
Mean ratio	0·85	1·61	0·48	0·85
CV%	42	—	—	47
RDU 3				
Number of projects	22	4	10	36
Mean ratio	0·97	0·15	1·71	1·09
CV%	54	67	—	99
RDU 4				
Number of projects	—	—	—	42
Mean ratio	—	—	—	1·16
CV%	—	—	—	55
Detailed study				
Number of projects	8	4	3	15
Mean ratio	1·51	1·22	2·07	1·63
CV%	38	100	—	45

percentage of the mean). Table 4 gives the corresponding results for the ratios of actual to initially estimated duration. For RDU 2, because of the large number of projects, it is possible to make an analysis by research areas, and results for three of these are given in Tables 3 and 4, to indicate the range of difference which can exist within one research organization. Area 1 is a relatively basic biological one, whereas Areas 10 and 12 are product and process development areas, the first concerned with a narrow range of products, the second with a wide range. The average costs and durations for the three areas (not given here) are not much different from those for the organization as a whole.

Table 4. Ratios of actual durations to estimated durations

	Normal	Abandoned	Altered	All
RDU 1				
Number of projects	57	13	14	84
Mean ratio	3·04	1·76	4·34	3·06
CV%	96	61	—	91
RDU 2				
Number of projects	156	37	27	220
Mean ratio	1·39	1·01	0·72	1·24
CV%	52	45	—	57
Area 1				
Number of projects	8	2	1	11
Mean ratio	1·00	1·15	1·08	1·03
CV%	41	13	—	34
Area 10				
Number of projects	21	12	3	36
Mean ratio	1·82	0·81	0·59	1·38
CV(%)	56	64	—	71
Area 12				
Number of projects	13	1	2	16
Mean ratio	1·15	1·43	0·42	1·08
CV(%)	22	—	—	33
RDU 3				
Number of projects	17	2	4	23
Mean ratio	2·58	1·75	3·83	2·72
CV(%)	50	121	—	52
RDU 4				
Number of projects	—	—	—	50
Mean ratio	—	—	—	2·38
CV(%)	—	—	—	62
Detailed study				
Number of projects	8	3	3	14
Mean ratio	1·69	1·95	2·00	1·95
CV(%)	50	94	—	53

The high values of the ratios for the altered projects in RDU 1 and RDU 3, which include extended projects, show the desirability of segregating projects of this sort, even though their effect on the ratios for all projects is sometimes offset by low ratios for the abandoned projects.

For convenient comparison, the main outcome/estimate ratios are summarized in Table 5, together with corresponding results for the Mansfield & Brandenburg, Meadows, and Thomas studies. Where classification has been possible (i.e., RDU 1, RDU 2, RDU 3, and the detailed study) only normal projects have been included. The mean cost ratios for the present studies range from 0·97 to 1·51, with CV's from 38% to 80%, and the mean duration ratios from 1·39 to 3·04, with CV's from 50% to 96%. Thus, there is a general tendency towards optimism, and a wide spread of project ratios about their

Table 5. Comparison of outcome/estimate ratios in nine studies

Study	Number of projects	Mean cost ratio	CV (%)	Number of projects	Mean duration ratio	CV (%)
RDU 1	57	1·46	80	57	3·04	96
RDU 2	162	1·07	48	156	1·39	52
RDU 3	22	0·97	54	17	2·58	50
RDU 4	42	1·16	55	50	2·38	62
Detailed	8	1·51	38	8	1·69	50
Mansfield & Brandenburg	45	0·96	40	—	—	—
Meadows A	23	1·34	82	—	—	—
Meadows B	29	1·99	105	—	—	—
Thomas	8	2·14	56	8	1·21	17

means. In every study, the duration ratio is higher than the cost ratio—in most, much greater—from which it is clear that, since the main part of the cost of most projects is labour, unexpectedly long durations must have been due to delays, rather than to unexpectedly high work content. There is no doubt that a part of the particularly high duration ratios for RDU 1 and RDU 3 was due to delays in arranging external collaboration, such as the use of production plant for experiments.

The Mansfield & Brandenburg cost ratios relate to an 'equipment manufacturer'; the mean ratio is as quoted by Meadows, and the CV is estimated from Mansfield's Table VII. It is uncertain, from the context, whether the data relate to final costs or to rates of expenditure; if the latter, then the mean ratio will tend to under-estimate the final cost ratio, if the projects last longer than estimated. In any case, however, the results are quite consistent with those of the present study.

The Meadows A and B studies relate to projects (probably all concerned with product development) in two commercial chemical laboratories. The projects have a mean actual cost of $10,000 for A, but only $1,670 for B. For present purposes, projects described as 'miscellaneous and technical failure' have been excluded, since most of them would presumably fall into the 'abandoned' category. The Meadows A results are quite consistent with those of the present studies, but the Meadows B results are rather high both in mean and in variability. It is not possible to tell how far either the A or the B results may be affected by the inclusion of projects with altered content.

The Thomas cost and duration ratios are for 10 instrument development projects in his Firm A, of which 3 have been amalgamated here because they are closely inter-dependent. The actual costs (i.e. not those adjusted for price changes) have been taken. Contrary to a statement (based on misunderstanding) by Allen & Norris, they are purely R & D costs, and do not include manufacture. Compared with the others, this study is notable for its high mean cost ratio, and for the low mean and variability of its duration ratios. Thomas's comment on the willingness of Firm A to put additional resources into projects, in order to complete them by a given date, suggests a possible reason for the reversal of the cost ratio–duration ratio relationship found in the present studies.

The distributions of the individual project cost and

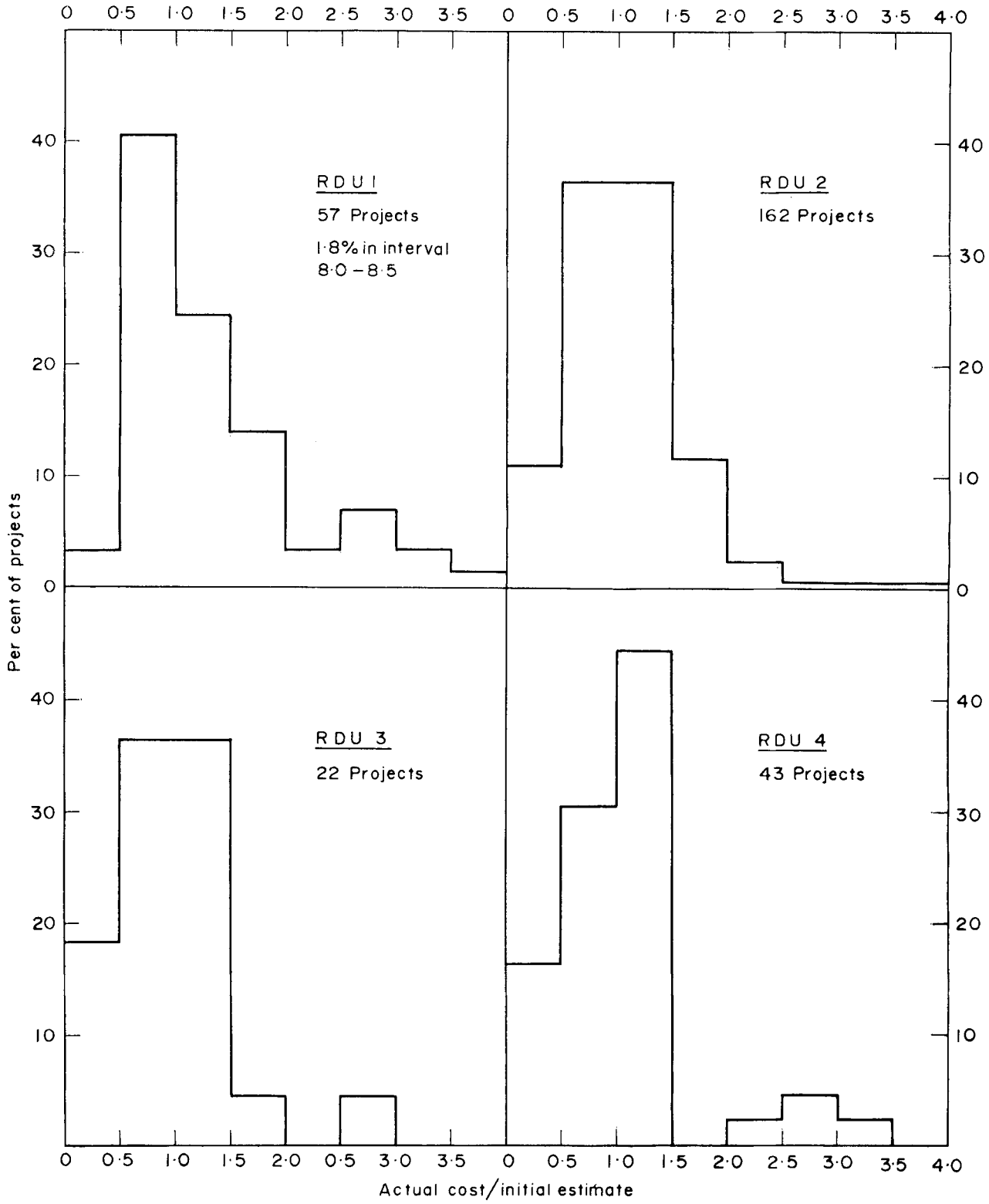

Figure 1A. Distribution of cost ratios

duration ratios for RDU 1, RDU 2, RDU 3, and RDU 4, and the cost ratios for Meadows A and B, are shown in Figures 1A, 1B, and 2. As might be expected, they are skewed to the right, though to varying extents.

MISCELLANEOUS POSSIBLE EFFECTS ON ESTIMATE ACCURACY

More expensive (and therefore generally larger and more complex) projects might be thought likely to present more difficulties in estimation than smaller and less expensive ones. Similarly, longer projects, stretching further into the future, might present more difficulties than shorter ones. Tests for these possible effects on the accuracy of both cost and duration estimates have been made in RDU 1, RDU 2, and RDU 3, by dividing the projects at the median estimated cost and median estimated duration, and comparing the two means. No significant effects have been found, except that in RDU 2 longer projects

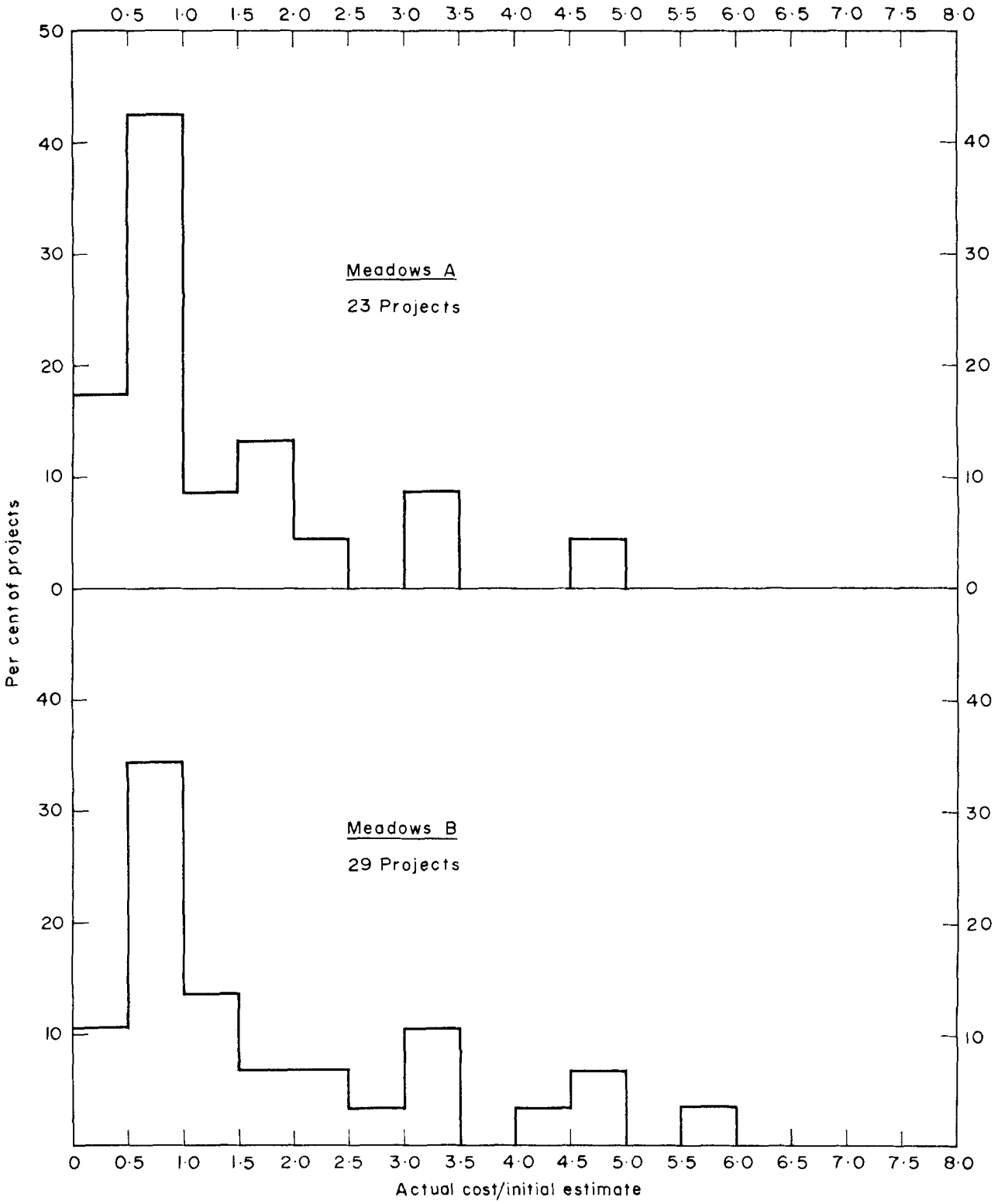

Figure 1B. Distribution of cost ratios

had more accurate duration estimates; the mean ratio for projects of 5 months and more was 1·14, compared with 1·62 for projects of less than 5 months.

In RDU 1 and RDU 2, attempts were made to sort projects into two groups along subjectively measured dimensions which might be related to uncertainty, and therefore to estimate accuracy. In RDU 1 the division was between routine projects (30%), where the work to be done appeared clearly foreseeable from past experience, and speculative projects (70%), where it did not. In RDU 2 the division was between more basic projects (20%), where the aim was background knowledge and understanding, and less basic projects (80%), where the aim was solution of a specific practical problem. Neither of these divisions produced any significant difference in estimate accuracy. There were differences between research areas in RDU 2, but these did not show any relationship to the character of the research, except that there was perhaps some tendency for product and process development projects to have higher duration ratios,

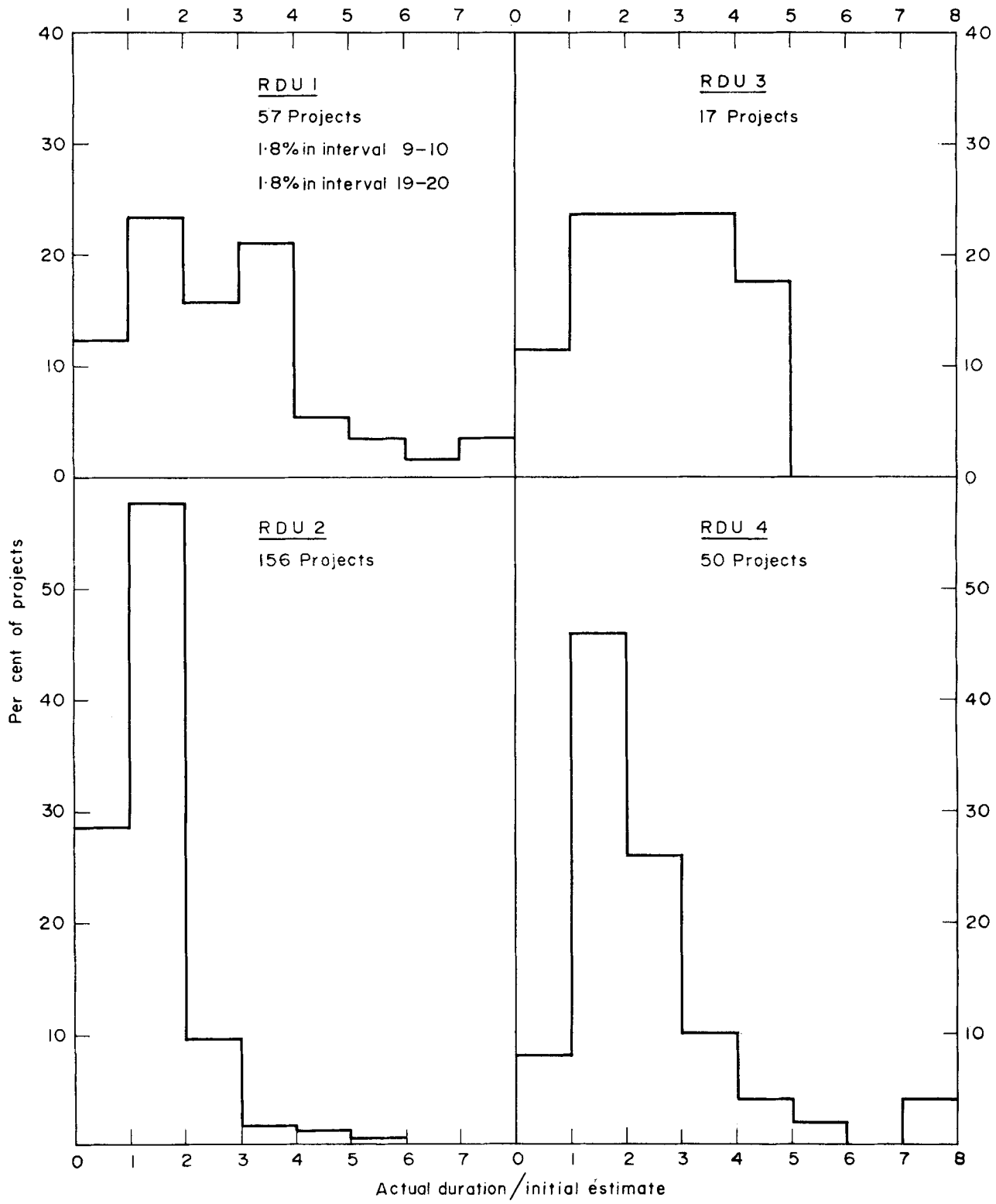

Figure 2. Distribution of duration ratios

possibly because of their greater dependence on external collaboration with manufacturing.

Finally, the projects in RDU 1, 2, and 4 were divided along the time dimension—in the case of RDU 2, into 4 parts—to test whether more recent projects had more accurate estimates than less recent ones, such as might result from some kind of learning effect in the research organization.

In RDU 3, the number of projects was considered insufficient for this purpose. No effects were found in RDU 1 or 2, but in RDU 4 there was a significant improvement in duration ratios, from 2·88 in less recent projects to 2·05 in more recent ones. This could have been due to increasing experience of estimation, or to increasing effectiveness of the planning and control system.

CHANGES IN ESTIMATES OVER PROJECT DURATION

Estimates made for reviews are available for many pro-

jects in RDU 1, 2, and 3, and provide a basis for investigating changes in the accuracy of estimates as projects move towards completion. The ratios of estimates to final outcomes are appropriate for this purpose, since they indicate the error with which the outcome is estimated, and tend to converge on unity at the completion date. The frequency of reviews varies from one study to another; in RDU 1 there are two reviews per project (on average), in RDU 2 there is one review per project, and in RDU 3 just over one. It will be remembered that the average duration of projects is much greater in RDU 1 than in RDU 2 or RDU 3.

this should remain constant over successive fractions of project duration. If it can be assumed that project expenditure tends to be proportional to time elapsed, then similar arguments can be applied to cost estimates.

The calculations made on this basis in Tables 6 and 7 show that in RDU 1 the mean error of both cost and duration estimates fell as the projects approached completion, but that the relative mean error remained fairly constant. It appears, therefore, that the knowledge and experience gained in the earlier parts of projects did not enable the cost or duration of the later parts to be estimated more accurately. This result is a little surprising,

Table 6. Changes in cost estimates over time

Time interval (fraction of duration)	0	0·001–0·199	0·200–0·399	0·400–0·599	0·600–0·799	0·800–0·999
Fraction of project incomplete (a)	1·0	0·9	0·7	0·5	0·3	0·1
RDU 1						
Number of estimates	57	12	35	28	32	10
Mean error (%)	35	48	27	25	13	4
Relative mean error (%) (b)	35	54	38	50	42	38
RDU 2						
Number of estimates	81	9	19	56	50	22
Mean error (%)	45	32	33	33	25	18
Relative mean error (%) (b)	45	36	48	66	83	184
RDU 3						
Number of estimates	22	0	6	9	8	5
Mean error (%)	65	—	47	21	41	30
Relative mean error (%) (b)	65	—	67	42	136	304

(a) Assuming that progress is proportional to time elapsed.
(b) Mean error divided by fraction of project incomplete.

Table 7. Changes in duration estimates over time

Time interval (fraction of duration)	0	0·001–0·199	0·200–0·399	0·400–0·599	0·600–0·799	0·800–0·999
Fraction of project incomplete (a)	1·0	0·9	0·7	0·5	0·3	0·1
RDU 1						
Number of estimates	57	12	35	28	32	10
Mean error (%)	51	56	38	30	15	5
Relative mean error (%) (b)	51	62	55	60	50	48
RDU 2						
Number of estimates	79	9	19	53	51	22
Mean error (%)	33	38	30	21	11	2
Relative mean error (%) (b)	33	43	44	42	37	21
RDU 3						
Number of estimates	17	0	4	9	6	5
Mean error (%)	50	—	50	29	22	8
Relative mean error (%) (b)	50	—	71	58	73	80

(a) Assuming that progress is proportional to time elapsed.
(b) Mean error divided by fraction of project incomplete.

An analysis of the initial and review estimates in terms of the fraction of the actual project duration in which they were made is given for RDU 1, 2, and 3 in Table 6 (for cost estimates) and Table 7 (for duration estimates). The 'mean error' here is the mean of the deviations of the estimate/outcome ratios from unity. If a number of estimates are made, say, during the middle fifth of the project durations, it is reasonable to assume that they were made at time 0·5. At this time, half the project duration is a known fact, so that it is appropriate to relate the error in the estimates of the project duration to the remaining half. More generally, the mean error divided by the future part of the project may be termed the relative mean error, and if forecasts are made with constant accuracy

but the results for RDU 2 and 3 are more surprising, since the relative mean error of the cost estimates actually rises, and the accuracy of estimation therefore falls, as the projects approach completion. The accuracy of the duration estimates is substantially constant, as in RDU 1. The explanation of the apparently perverse behaviour of the cost estimates is probably that, with only about half the projects in RDU 2 and 3 being reviewed, less regard is paid to the correction of estimates, and previous cost estimates are allowed to stand which in the light of changing knowledge ought to be altered. Disparities between duration estimates and the known state of the project are perhaps more blatant and less easily ignored.

The data in RDU 4 do not permit quite the same form of analysis as the other studies. It is possible, however, to compare successive estimates of the duration of the later stages of projects, and the results again lead to the conclusion that the accuracy of duration estimates does not improve, but remains substantially constant as the projects move towards completion.

THE PATTERN OF EXPENDITURE OVER PROJECT DURATION

The data assembled for the purpose of comparing actual costs with estimates also enable an examination to be made of the pattern of expenditure over time. One reason why this is of interest is that the method of analysis applied earlier to changes in the accuracy of cost estimates over time depends on a reasonable degree of linearity in the average relationship between expenditure and time. A further reason is that suggestions have been made (e.g. by Frangipane, 1970) that if a consistent pattern can be demonstrated, this should be used to correct the final estimates by reference to the difference between the actual costs incurred up to the current stage and the expenditure predicted from the pattern. Thus, if the pattern was a particular form of curve, the new estimate of final cost would be given by the end-point of the curve passing through the point representing actual cost to date. Such a method is only available, of course, if one knows what fraction of the ultimate duration of the project has elapsed, and for most of the projects in this study the accuracy of duration estimates has been shown to be less than that of cost estimates. In a situation where, because of the particular importance of time, it was known that great efforts, including if necessary the use of additional resources, would be made to complete a project on time, the method might be more useful.

In the present studies both scatter diagrams and numerical methods have been used to examine the relationship between expenditure and time. Figures 3A and 3B show plots of all the cost statements made for reviews in RDU 2 and 3 (expressed as ratios to final cost) against the time of the review (as a fraction of the actual project duration). For this purpose all the projects in RDU 3, with or without initial estimates, can be used. The plot for RDU 2 suggests some tendency for expenditure to lag behind time, especially about the middle of the projects, but the scatter of the points is very wide. A corresponding plot for RDU 1 (given by Allen & Norris) is very similar in appearance. The plot for RDU 3 is also similar, except that expenditure tends on average to lead time in the middle stages. The data in RDU 4 do not lend themselves to this type of analysis.

Examination of the patterns of individual projects provides many examples of the form which, from theoretical considerations, might seem most likely—an S-curve, implying a delay in building up to a maximum effort, and then a decline to a final period of report-writing and tidying up. Unfortunately, there are as many examples of other patterns, such as a brisk start, followed by delays and interruptions, loss of interest for a time, and then a final effort to bring the work to a conclusion. Differences such as these account for the wide scatter around the diagonal line in Figures 3A and 3B, and it seems that, if a relationship is to be assumed between cost and time, a simple proportional one will often be adequate.

This conclusion is also supported by the numerical results given in Table 8. Here, mean values of costs reported at reviews are given, as ratios to the final costs, for five time intervals covering the duration of the projects. The mid-point of the time interval will of course be equal to the expected fraction of final cost expended at that point,

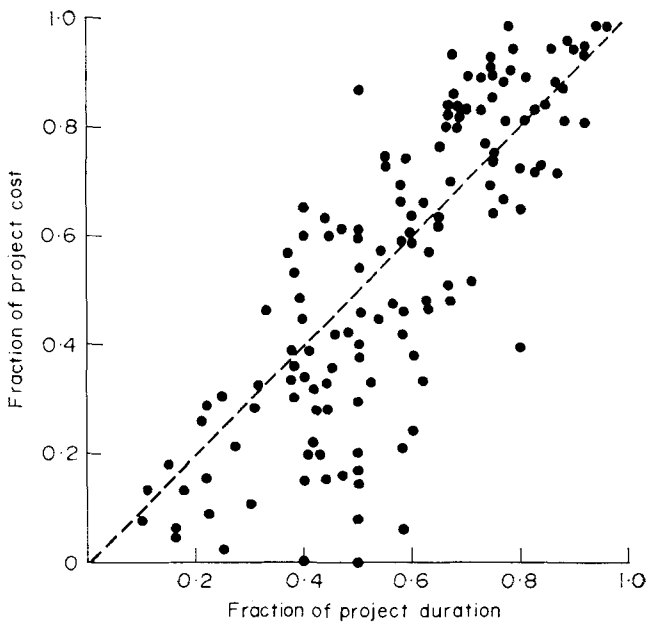

Figure 3A. Pattern of expenditure over time, RDU 2

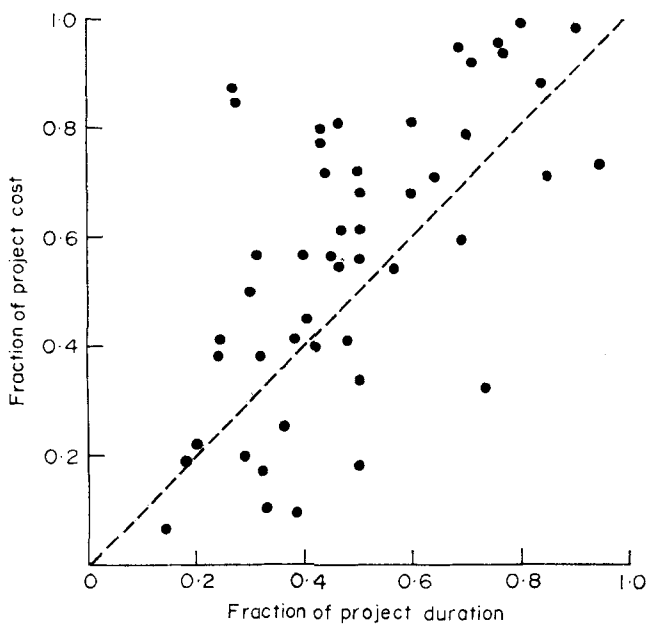

Figure 3B. Pattern of expenditure over time, RDU 3

if cost is proportional to time. For RDU 1 and 2, the actual mean costs are very close to this, but those for RDU 3 show a fairly constant lead in the three middle time intervals. There is no S-shape, but there is an upward convexity.

FINAL COMMENT AND SPECULATION

The results of this study, as of others, confirm that a general tendency towards optimism is an important cause

Table 8. Patterns of expenditure over projection duration

Time interval (fraction of duration)	0·000–0·199	0·200–0·399	0·400–0·599	0·600–0·799	0·800–0·999
Mid-point of time interval	0·1	0·3	0·5	0·7	0·9
RDU 1					
Number of reviews	25	31	28	23	14
Mean fraction of final cost	0·11	0·31	0·47	0·68	0·82
RDU 2					
Number of reviews	6	18	50	43	21
Mean fraction of final cost	0·10	0·30	0·41	0·72	0·83
RDU 3					
Number of reviews	2	15	18	10	5
Mean fraction of final cost	0·13	0·37	0·57	0·76	0·86

of inaccuracy in estimates for R & D projects, although some organizations manage to avoid it in cost estimates (e.g. RDU 2 and 3). A tendency towards optimism may be a general human characteristic, but the evidence suggests that its operation is modified by factors which vary from one organization to another. The nature of these factors requires further investigation, but it is probable that the relative penalties for optimism and pessimism play a large part. If the management expects and allows for optimism, attractive initial estimates are necessary if a project proposal is to be authorized, and subsequent revisions may be obtainable without much difficulty or disapproval. Thomas comments that in his study the engineers recognized that they tended to be optimistic in their forecasts because otherwise their proposals might not be accepted. On the other hand, if initial estimates are taken at their face value, and serious disapproval attaches to exceeding them, any necessary compensation for optimism may be made by the proposer himself.

A subsidiary result which is interesting in this connection was obtained in RDU 3, where, it will be remembered, estimates of costs to first review were acceptable, instead of costs to completion. A comparison of these estimates with the actual costs to review, for 32 projects which were reviewed at the appointed time, gives a pessimistic mean outcome estimate ratio of 0·61. On the other hand, the same estimates prove to be quite good estimates of cost to completion—mean ratio 1·11. The mean ratio for estimates of *completion* cost in the same study is 0·97. A possible interpretation of this unexpected result is that the people concerned were not really estimating the cost for a stage of the project, but rather the cost for which they hoped to arrive fairly near to the objective, while allowing for the possibility that they might have to request further funds at the review.

Where estimates of duration are concerned, the main reason for inaccuracy is not optimism about the resource requirements of the projects, but optimism about the amount of other work to be undertaken at the same time, and about the availability of external contributions, such as equipment to be bought, or facilities to be used which are not under the control of the research management. There is a general tendency to accept (often under pressure from other departments) more work than the available resources can perform. It is probably necessary in many cases, however, to undertake sufficient projects to produce some degree of delay due to overloading, since otherwise the delays due to uncontrollable external factors would sometimes cause resources to be unemployed. Thus, a mean excess of actual durations over estimates may be desirable, though not to the extent found in the studies.

Even where estimates free of overall optimistic or pessimistic bias can be obtained, these remain large individual project errors. These may, of course, be partly due to the bias of individuals, but probably they are mainly due to ignorance of the amount and kinds of work that will be required, of the results that will be obtained, and of the time that will be taken. Clearly, there must be an underlying minimum of error due to the inherent uncertainty of research, but there may also be components due to failure to think systematically about the likely course of the projects, or to failure to use all the available sources of information.

If it can be assumed that a particular degree of bias is characteristic of an organization, and affects all its projects equally, the outcome/estimate ratios for individual projects can be split into a general bias component and a residual error peculiar to the project, and this has been done for the RDU 1, 2, 3 and 4, the 'detailed', the Thomas, and the Meadows A and B studies. It has been assumed that the bias is a constant proportional effect; constant absolute effects, and mixtures of absolute and proportional effects (e.g. an ordinary linear regression equation) have been rejected as less plausible. What remains is then a distribution of positive and negative errors around a mean of zero. These are all more or less skewed to the right, and a more symmetrical distribution is obtained by taking logarithms to base e, though sometimes this over-corrects and substitutes one direction of skewness for another. As an illustration, Fig. 4 shows the effect of these two transformations on the distribution of ratios of actual to estimated durations in RDU 2.

Table 9 shows the assumed constant bias factors for the various studies, and also, as a measure of the residual error, the standard deviation of the transformed ratio distribution. For cost ratios, the residual errors of RDU 1 to 4, and of the Thomas study, all fall within the range 0·53 to 0·63, though that for the detailed study is rather lower, and those for the two Meadows studies, which may be affected by projects with voluntarily increased content, are rather higher. The smaller numbers of studies with duration ratios also give results within a fairly narrow range, with the exception of the Thomas study, where special efforts were made to complete the projects by a given date, even at additional cost. A stan-

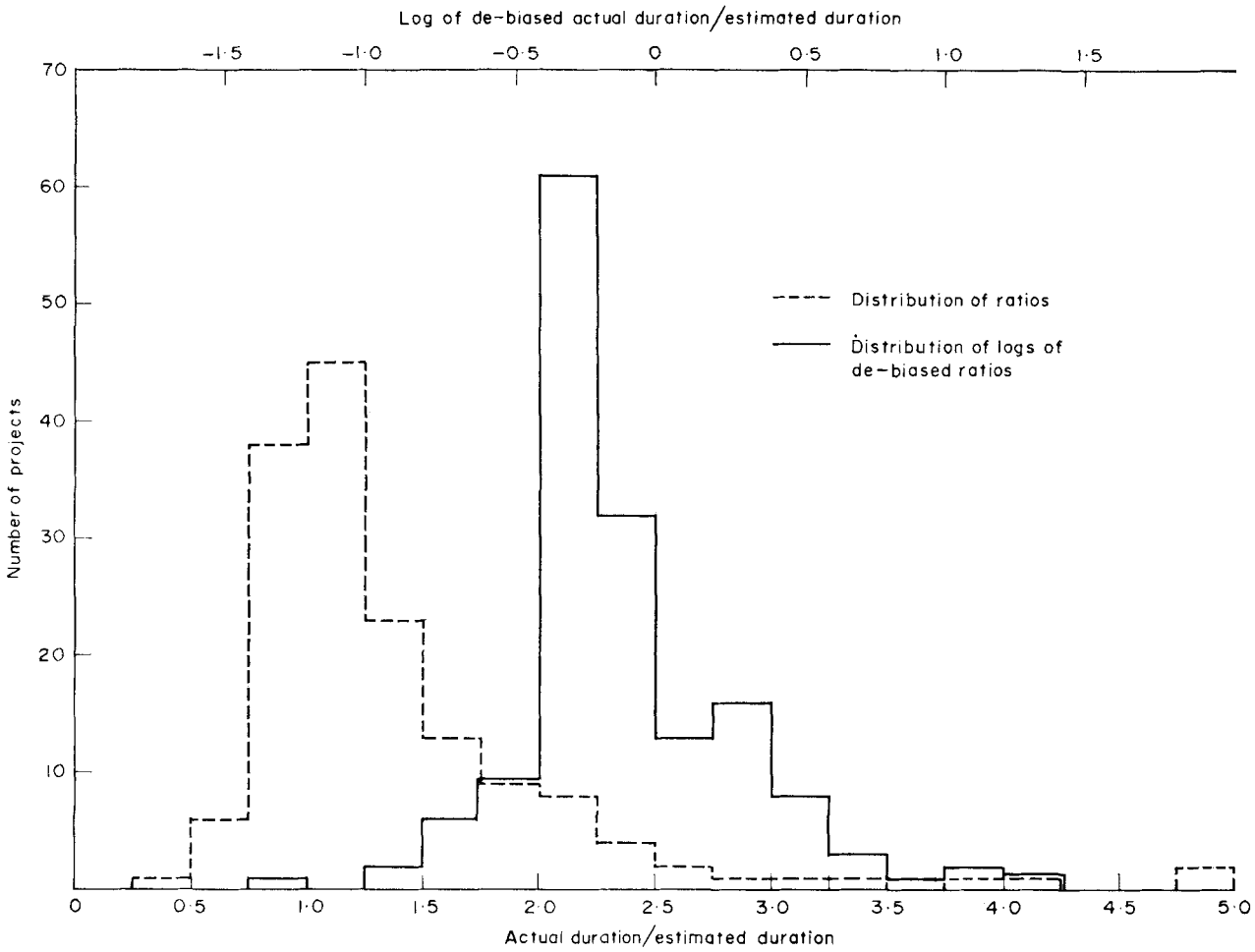

Figure 4. Original and transformed ratio distributions (RDU 2)

Table 9. Bias and residual errors of transformed ratios

Study	Cost estimates			Duration estimates		
	No. of projects	Bias (%)	Residual error (a)	No. of projects	Bias (%)	Residual error (a)
RDU 1	57	+46	0·56	57	+204	0·71
RDU 2	162	+7	0.53	156	+39	0.41
RDU 3	22	−3	0.61	17	+158	0.53
RDU 4	42	+16	0.59	50	+140	0.52
Detailed	8	+51	0.36	8	+69	0.50
Thomas	8	+114	0.63	8	+21	0.17
Meadows A	23	+34	0.76	—	—	—
Meadows B	29	+99	0.86	—	—	—

(a) This is the standard deviation of the transformed ratio distribution.

dard deviation of 0·55 for the transformed cost ratios (which is the middle of the range in which most of the results lie) implies that, even in the absence of bias, the range within which most individual projects lie stretches from as low as one-third of the initial estimate to as high as three times.

It would be too much to suggest that the similarity of the results obtained here from a variety of organizations, once the bias has been removed, implies that a measure has been obtained of the basic and irreducible uncertainty of the cost and time aspects of industrial R & D. The nature of the individual project errors requires further investigation. Nonetheless, the degree of similarity is striking, and suggests that the system of causes at work is common to many research organizations and types of research.

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