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**Working Paper — Digitized Version**

## Laboratory experiments on the efficiency of decomposition principles in decentralized planning

Manuskripte aus den Instituten für Betriebswirtschaftslehre der Universität Kiel, No. 110

**Provided in Cooperation with:**

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*Suggested Citation:* Leichtfuß, Reinhold; Schmidt, Reinhart (1982) : Laboratory experiments on the efficiency of decomposition principles in decentralized planning, Manuskripte aus den Instituten für Betriebswirtschaftslehre der Universität Kiel, No. 110, Universität Kiel, Institut für Betriebswirtschaftslehre, Kiel

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Nr. 110

Laboratory Experiments on the Efficiency of  
Decomposition Principles in Decentralized Planning

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and  
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May 1982

Paper presented at the Third European Symposium of the European Association of Agricultural Economists and the Department of Agricultural Economists at the University of Kiel on May 28th, 1982.

Special section on "Coordination in multidivisional firms".

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Financial support for the research project has been provided by the Deutsche Forschungsgemeinschaft (DFG), Research Section "Empirische Entscheidungstheorie".

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## Literature

## 1. Introduction

The analogy between the decomposition principle of Dantzig and Wolfe [9] and decision-making in decentralized organisations was pointed out by Almon [2] as early as 1963. Since then an enormous amount of academic work has been directed towards the examination and development of different algorithms for the solution of large systems. Research on implementation in real organisations, however has only been intensified in the seventies. Due to the simulation studies of Burton and Obel [7], Christensen and Obel [8], Ljung and Selmer [18], Schiefer [27] valuable insights into the computational performance of several decomposition algorithms have been gained. Moreover, Burton and Obel studied the rational exploitation of a priori information available in organizations for the purpose of finding good starting strategies.

Other studies have been concerned with the introduction

- of uncertainty (e.g., Freeland/Schiefer [10])
- the problems of cheating (e.g., Jennergren/Müller [14], Schmidt [28])
- incentive systems, in particular to prevent cheating in decentralized decision-making (e.g., Jennergren [15], Groves/Loeb [12]).

This research should be advanced to resemble the conditions in real-life organisations more closely.

Nevertheless, there has been little empirical investigation into the implementational problems involving human subjects as decision makers. To our knowledge, Jeffrey Moore was the only one who had so far conducted laboratory experiments in this field [21]. In a way he was also concerned with good starting strategies, since he examined comparative managerial performance of the coordination agents at the top under the price and budgeting schemes. The results demonstrated a superiority of the human beings as central coordinators over the algorithm in early iterations. He did not consider behavior and decisions of the divisional managers. Nonetheless, his focus was on the relative performance of different decomposition principles. Moore did not investigate other coordination principles than mathematical algorithms.

To our understanding research on the following issues is essential:

- (1) The efficiency of a coordination procedure modelled on decomposition procedures in comparison with coordination principles existing in actual decentralised organizations.
- (2) The acceptance of a coordination procedure - e.g. a decomposition procedure - by the members of an organization: behavioral aspects must be taken into account.

The first issue follows from the experience that people want to be convinced that something new is better than what they are doing at the moment.

Under this issue we are primarily interested in what we could call "technical efficiency", i.e. performance and costs of the coordination procedures. However, good model-based plans with high values of the underlying objective function have not yet been implemented. We therefore have to be aware of possible different effects of coordination procedures on the implementation phase [3]. To what extent do coordination procedures reinforce the actual implementation of the planned results?

Decomposition procedures are said to have several properties of decentralised coordination, i.e. some kind of autonomy at the divisional level resulting in positive motivational stimuli [1]. Do people recognize these properties? How do they classify them compared to these properties in other procedures?

To cover all these criteria, we have developed a concept for measuring the overall efficiency of different coordination procedures. The acceptance by the members of an organisation is one important component of the concept. In fact, acceptance is crucial within any decision process that involves methods of operations research (e.g., [22], [29]).

## 2. Hypotheses and Experimental Design

### 2.1. Theoretical Concept and Hypotheses

To meet the indicated objectives, laboratory experiments seem to be the appropriate device for research in the first stage. Since it is hard, if not impossible, to measure the efficiency of coordination instruments in all their applications and in every respect, we have chosen their application in the field of capital budgeting. This seems to be the major coordination problem in real world divisionalised firms.

We designed three different coordination procedures (CP) which can be described as follows:

CP1: Coordination within a computer-aided conference based on methods in actual practice.

CP2: Coordination by man and machine, i.e. a decomposition algorithm combined with intervention by man.

CP3: Coordination only by means of a decomposition algorithm.

In each procedure, plans are coordinated within the framework of the multiperiod capital budgeting model of Weingartner and Hax [34], [13]. Instead of a perfect capital market we introduce upper limits on borrowing. At this stage cash flows and other data are assumed to be certain. The data are the same for each procedure. The firm's goal is the maximization of the horizon value at the end of a planning period of five years. This planning period is consistent with corporate practice.

Only the central unit has access to external capital markets but does not have complete knowledge of the investment opportunities in the divisions.

Our main hypotheses are

- (1) The three coordination procedures differ as regards their overall efficiency.
- (2) The ranking of the coordination procedures varies with different dimensions of efficiency.
- (3) The coordination by man and machine is superior to the other coordination procedures.

Furthermore, we developed a number of hypotheses concerning specific aspects which we shall discuss later.

Our attention in this paper will be focused on the overall efficiency of procedure 3 and the connected hypotheses.<sup>1)</sup>

## 2.2. Detailed arrangement of the coordination procedures

CP1 resembles methods in actual practice in a simplified form. The technical aid of a conference by the computer introduces a supporting element to the coordination by human beings. The design is oriented to field research and to reports on the practice of coordination and capital budgeting (e.g., [4], [5], [19], [23], [25], [26], [30], [32], [33], [35], [36]). Therefore, investment projects are treated differently depending on the initial expenditure. Large projects (initial expenditure amounting to DM 5 million or more) are being presented by the division heads within the finance committee. The central unit and the remaining division managers in their turn have the opportunity to make a comment on the presentation of each single project.

After the review of all large projects, the committee is to decide upon their selection. Before, the members are given an overview of the total amount required by small projects of the whole firm. Details of small projects still remain with the divisions. It is up to them to inform the rest of the firm of their "advantageous" opportunities.

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1) See page 11.

In this way the decision makers are faced with a conflict between approving large projects and, by that, reducing the amount of available funds for small projects. The necessity for capital rationing has been made clear earlier. The remaining funds are allocated to small projects in the order of their internal rates of return. Despite the justified theoretical criticism of this measure, it has proved superior to many other traditional measures in simulation studies [16].

On the whole, this coordination procedure leaves wide scope for the argumentational skills of the committee members. Moreover, their involvement in the decision process is comparatively high.

To a lesser extent this applies to CP3, the algorithm. As a representative example for decomposition principles, we implemented that of Maier and Vander Weide [20] which is both budget and price directed.<sup>1)</sup> In this way we wanted to use properties of the two basic coordination principles. The involvement of budgets corresponds to current corporate practice [e.g., 11].

Moreover, the algorithm proved to converge reasonably well under the conditions of capital rationing and even better when no limits on borrowing are presumed [17]. The simulation-based research will be advanced to look at further characteristics of the algorithm.

The central unit opens the coordination process by sending transformation factors and budgets to the divisions. In the pure algorithm form, the central unit starts with shadow prices on the basis of the lending rate, which represent the minimum yield on funds when investing them on the capital market. The total available funds are allocated to the divisions at equal shares. The central unit calculates prices and budget allocations with the help of linear programs. These are urged to calculate their optimal investment programs on the basis of the values received. The calculation is also

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1) Thanks for the programming of the coordination procedures are due to Gerold Dählmann and Klaus Nissen. Jens van Almelo provided an intertask communication facility for the connection of several terminals. We also thank Lutz Ahrens for his skill in putting the finishing touches to the intertask communication.



done by the computer using linear programs as soon as the division managers have "digested" the planning data and given the signal for solving the problem.

They submit two tentative plans to the central unit: One without considering the budget constraints and one in line with the allocated funds.

The following figures give an example of the information exchange between the central and the divisional units:

```
Please calculate your optimal investment program
on the basis of the following transformation factors:
t=1 (1982) : 2.7634
t=2 (1983) : 1.452
t=3 (1984) : 1.210
t=4 (1985) : 1.100
t=5 (1986) : 1.000

Within each period you must not violate the
budget constraints stated below

Period      Admissible demand      Funds to be
            of funds              transferred to
                                   the central unit

1           10480.00             0.00
2           0.00               3426.50
3           0.00               3917.80
4           0.00               3894.20
5           0.00               630.00

Please inform us as soon as possible about your
demand of funds for each period as well as your
contribution to the overall objective of the company.

By pushing "return" you achieve the first optimization
of the investment program of your division
(without compliance with budget constraints)
```

Figure 1: Request by the Central Unit to the Divisional Units for the Calculation of Plans.

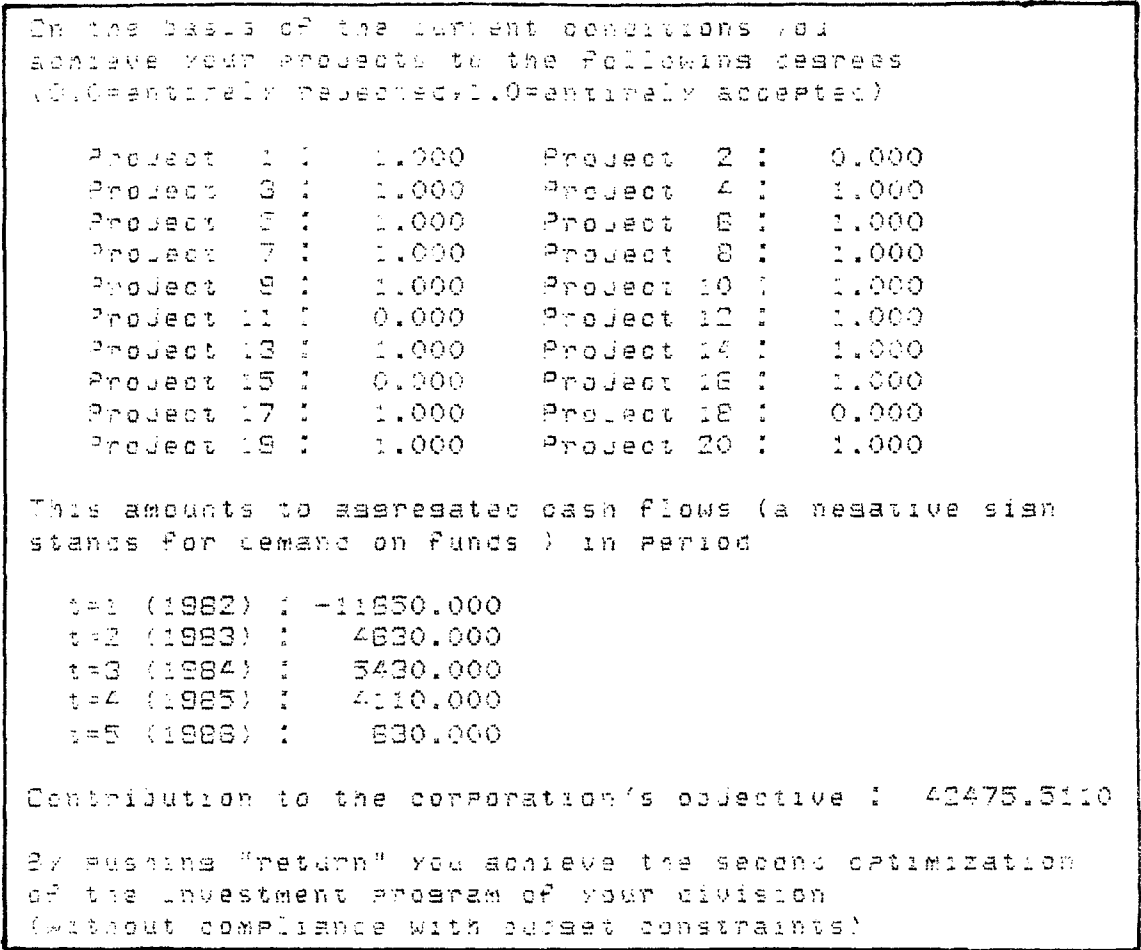


Figure 2: Plan of a Division without Consideration of Budget Constraints

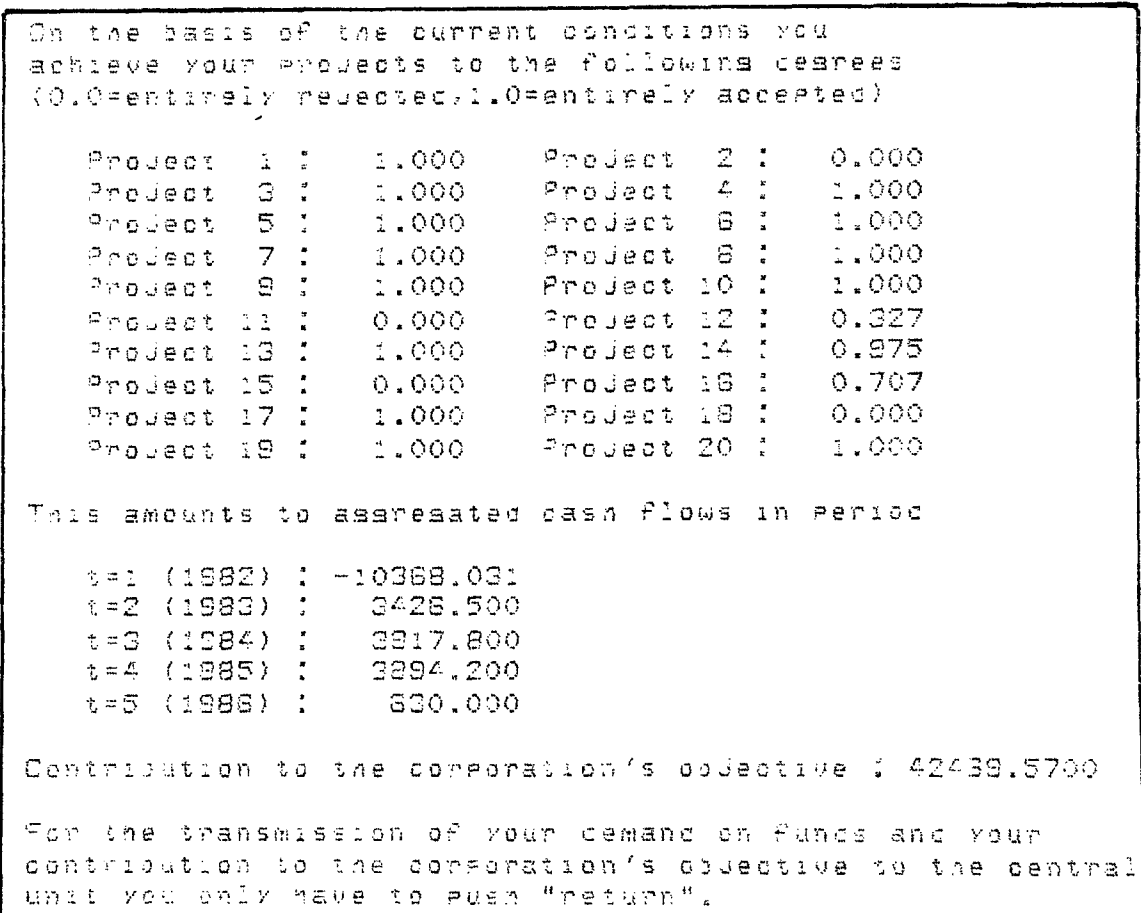


Figure 3: Plan of a Division in Compliance with Budget Constraints

In contrast to CP1, the central unit gets no detailed information, not even on large investments. The informational autonomy of the divisions therefore remains higher. This refers to both, CP3 and CP2.

Coordination procedure 2 combines the decomposition algorithm with heuristic intervention by man. Intervention is at this stage possible at the beginning of the process, i.e. central coordinators are to find good starting values by optimally exploiting all the information available.

Moreover, all committee members decide on the continuation or termination of the coordination process after each cycle. A cycle consists of a complete round of information exchanges between the central unit and the divisions. Thus, CP2 offers more decision-making opportunities than just decide on the starting strategy. The procedure achieved very good results in several dimensions of the efficiency concept. It will be discussed in more detail in a later paper. In the following, we concentrate on the results of the pure decomposition procedure and contrast them with CP1.

### 2.3. The Experimental Setting

The experimental task was placed in a multidivisional firm that was modelled on an actual corporation in Germany (Mannesmann). Two organizational levels consisting of one central unit and three divisions were incorporated.

64 students of finance at the University of Kiel participated in the experiments which made up 16 coordinating groups. They all had to coordinate under all three different procedures in order to enable them to make a comparative judgement. Two weeks before the experiments took place, the participants received a general description of the firm, its organizational structure, the business and development of the divisions in the past as well as projections for the future which are generally known within the firm. They did not get detailed information on investment projects or capital market conditions at that time. Furthermore, the paper contained a description of the coordination procedures.

All participants were familiar with traditional capital budgeting methods as well as mathematical programming models, in which they had been particularly trained in advanced courses. Moreover, they had been introduced to decomposition methods as coordination devices. In fact, the principle of Maier and Vander Weide [20] was discussed thoroughly in the advanced courses. Additionally, all students had at least some experience in the use of the computer. The calculation of internal rates of return and some other measures of investment projects with the aid of computer programs was compulsory within the course.

Due to the thorough preparation we think we have strengthened the external validity of our experiments. Moreover, contemporary students of finance are the potential coordinators and division heads of tomorrow, which underlines the usefulness of such experiments. Nevertheless, we intend to conduct experiments with practitioners as well.

Half an hour before the start of the actual coordination process, detailed data on investment projects and financial projections for the planning period were handed out to the participants. The data-descriptions were considered as preparatory material for the decision-makers provided by the planning departments of the central and divisional units.

Only then were persons randomly assigned to particular functions within the firm (central coordinator, division manager). This was to prevent the formulation of strategies by groups in beforehand.

The experiments were called "exercises in capital budgeting in the divisionalized firm" in order to avoid an experimental character. The average duration of an experiment including the preparation and the final questioning was approximately 4.75 hours. There were refreshment-breaks between the single procedures.

### 3. Some Results

In the following we report on several criteria that are relevant in our concept of the overall efficiency.

An overview of some criteria is presented in Table 1:

TABLE 1  
Values for Some Efficiency Criteria for the Evaluation of  
Coordination Procedures (64 Participants of Laboratory Experiments)

		CP1	CP3
Understandability of the solution process (7) completely understandable ... ...not at all understandable (1)	$\bar{x}$	5.844	4.781
	s	1.348	1.608
Understandability of the information exchange (7) completely understandable ... ...not at all understandable (1)	$\bar{x}$	6.031	4.469
	s	1.321	1.436
Participation within the decision process (7) fully involved ... ...not at all involved (1)	$\bar{x}$	5.828	2.266
	s	1.464	1.994
Level of autonomy in decision-making (7) complete autonomy ... ...complete lack of autonomy (1)	$\bar{x}$	5.406	2.375
	s	1.191	1.621
Horizon value of the capital budget	$\bar{x}$	98258.	104552.
	s	3860.	0.
Satisfaction with the result of the coordination process (7) completely satisfied ... ...not at all satisfied (1)	$\bar{x}$	3.969	5.703
	s	1.976	1.608
Identification with the final decision (7) active support ... ...attempt to somehow achieve rejected projects (1)	$\bar{x}$	5.146	5.771
	s	2.231	1.640

CP1 = Conference; CP3 = Decomposition Algorithm

In Table 1 means and standard deviations are reported because they give a first impression of the difference between CP1 and CP3.

The null hypothesis within each criterion is that there is no difference between the coordination procedures CP1 and CP3.

A closer look at the experimental setting leads to the following: We have related samples, which is an advantage because in this way deviations between groups present in the case of independent samples are omitted [6, p. 181], [24, p. 219 f.]. Furthermore, not all the data are drawn from a normal population.<sup>1)</sup> Therefore, the non-parametric analysis of variance of Friedman is the appropriate statistical test in the k-sample case ( $k \geq 3$ ). To investigate CP1 and CP3 for significant differences we applied the non-parametric test of Wilcoxon.<sup>2)</sup>

Although the subjects were comparatively well trained as regards decomposition theory, they regarded the solution process as well as the information exchange in CP1 as being easier to understand than in CP3. The null hypothesis was rejected with both criteria at the 0.001 level. The result is not surprising in view of the complexity of the decomposition algorithm.

Additionally, we asked the participants whether they perceived a lack of specific information as well as missing possibilities to pass on information in the course of each CP. Another question concerned data redundancy.

In view of the often voiced criticism against decomposition methods not to resemble the complexity of coordination<sup>3)</sup> we hoped to get some insights into what people really missed.

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1) According to the Kolmogorov/Smirnov goodness of fit test the null hypothesis (normal distribution) had to be rejected for some variables.

2) We also performed the t-test and obtained appr. the same level of significance within each criterion of Table 4.

3) Sweeney et al.: "The information exchanges in organizations are more detailed than the mere passing of dual variables." [31, p. 1498].

Note that the students were free to make their point clear. This strategy has the disadvantage that people may not be aware of the whole range of information they could have access to. On the other hand, we prevented the suggestive character of a presented list of possible further information. In a repetition of the experiments we might use the second alternative. The answers may give some hint for future shaping of decomposition-based coordination procedures.

Again, not to our surprise, many statements underline that the coordination process in CP3 was not completely understood and that the participants would like to know more about it. Such information requests constitute the first class of statements on perceived shortcomings of CP3.

Examples: "The calculations of the central unit remained in the dark.",  
" The calculations were difficult to follow."

A second class can be labelled as "lack of detailed and non-quantifiable data". Thus, central units had wanted detailed information at least on large projects. Others objected to a lack of qualitative data at all. Missing detailed information on other divisions is also regretted by some division managers. On the whole, people missed specific data rather than thinking of data redundancy. They demanded a more comprehensive supply of decision-supporting information.

A third class of statements concerns lacking opportunities to pass on information, or to influence other members of the organization:

Examples: "It was not possible to bring in all the data for my projects.",  
"Information about developments in other divisions would have been useful.",  
"No possibility to influence other divisions."

The bulk of objections most often voiced falls into this category.

The question concerning redundancy revealed a (probably) negative feature of decomposition principles that could, however, be overcome.

It is the repeated call upon a division to submit new tentative plans without remarkable changes. This gives rise to the hypothesis that people do accept additional iterations as long as there is a "noticeable" improvement in the objective function. They are not however readily prepared to calculate further plans if improvements seem unlikely. A termination of the process before the optimum is reached can solve the problem.

The number of presentations of tentative solutions was also considered too large by some of the participants. In combination with the proposal to let the process run and submit only the final result to the management, this could give rise to a reorganisation of the whole process. I.e., if models exist at the central as well as at the divisional level and there is an agreement on their appropriateness, the solution process could be managed by the planning departments. The top management need not be involved in the entire course of the process.

The number of acceptable iterations has been an extensively discussed issue. There is a wide agreement in the literature that the number must not be "too large". Some authors suggest two or three iterations. Burton and Obel [7] examine the efficiency of several algorithms within the first five iterations. But we do not know the number of iterations cycles that people - actually confronted with such a procedure - might be willing to go through.

We therefore asked the participants what number they conceived acceptable in a coordination problem such as they had just solved on a long-term basis. Note that no recommendation at all was made to the students.

The mean is 4.56 ( $s = 2.49$ ), which is surprisingly high. The responses vary on a range from 2 to 15. We asked one central coordinator who would have accepted 15 cycles for his reasoning: "If we can reach the optimum after 15 cycles I am willing to perform 15 cycles". Together with the reflections above, this suggests that the critical number of cycles is not a dogma. Attitudes can be influenced by education of coordinators, which is easier if the management need not be involved in all information exchanges.



The above-mentioned uneasiness with the passive role that the divisions in particular played in CP3 is manifested in the answers to two questions. These questions were on the perceived involvement in the decision-making process and the level of autonomy in decision-making. These aspects, necessarily linked with decentralized coordination, are often claimed for decomposition principles in general and resource directive principles in particular. In both cases the null hypothesis was rejected at the 0.001 level. CP3 was conceived to offer much less opportunity for participation in the decision-making process than CP1 did. That holds even though the "role-book" told the central coordinator that he had once introduced the decomposition principle to coordinate plans. The divisions were told to be free to choose their best plans within the final budgets. That means, no portions of previously submitted investment plans were made compulsory as it is the case in the original Dantzig/Wolfe principle.

Despite the inferior performance of CP3 on the motivational side, the participants expressed a significantly higher satisfaction with the final decision reached using CP3. The null hypothesis was rejected at the 0.001 level: The coordination procedure does have a significant impact on the level of satisfaction with the coordination result. In view of the significant difference between the horizon values any other outcome would have been a surprise.

Nevertheless, this could not turn the tide of preference-rankings in favour of CP3 (see table 2).

TABLE 2  
Preference-Ranking from the Division's Point of View

Ranking	Number of votes	
CP1 > CP2 > CP3	38	45
CP1 > CP3 > CP2	7	
CP2 > CP1 > CP3	7	12
CP2 > CP3 > CP1	5	
CP3 > CP1 > CP2	2	6
CP3 > CP2 > CP1	4	
	63	63

(One response with equal rank 2 for each procedure)

The null hypothesis was rejected at the 0.001 level.

From the division's point of view, CP1 was considered superior to CP3. Obviously, the divisions believed CP1 to serve their interests best. This might be due to the imagined ability to influence other divisions and the central unit in favour of the own projects. There is much evidence that participants are convinced of the superiority of their own arguments. CP3, however, was believed to deprive the divisions of this weapon. The poor preference ranking was somewhat of a surprise, since every division achieved a higher horizon value in CP3 than it did in CP1. Division three in fact increased its horizon value with CP3 as opposed to CP1 by appr. 30 % on average.

We also asked the students to state their order of preference from the corporation's point of view: "Which CP do you consider best from the corporation's point of view?" Preference-rankings are reported in Table 3.

TABLE 3  
Preference-Ranking from the Corporation's Point of View

Ranking	Number of votes	
CP1 > CP2 > CP3	18	24
CP1 > CP3 > CP2	6	
CP2 > CP1 > CP3	12	15
CP2 > CP3 > CP1	3	
CP3 > CP1 > CP2	3	22
CP3 > CP2 > CP1	19	
	61	61

(Three responses with equal ranks for each procedure)

Here the null hypothesis could not be rejected at the 0.05 level. One can take this as a result which speaks for formal methods. It is further supported by the response to the question on the identification with the decision. The precise wording of which is: "Would you actively support the coordination decision or instead try to achieve rejected projects in some way". The question was asked for all CP's. Here the null hypothesis could not be rejected at the 0.05 level, i.e. the CP does not have a significantly different impact on the behavior in the achievement phase.

This can be considered a positive result as regards the applicability of formal methods. Possible emotional inhibitions to using advanced methods could not be proved to result in a negative impact on the actual achievement of the plan. However, further inferences are not to be drawn from this result due to the unavoidable limitations of laboratory experiments.

Another result points two ways. We asked people whether they were prepared to accept a coordination procedure in which they benefited from higher shares in profits and made sacrifices as regards autonomy in decision-making. The mean is 4.94 (7 = Yes, 1 = No, in no case), i.e. there might be a slight tendency to accept a highly formal method if it promises more money. However this tendency is not overwhelming so that the way of a higher integration of people into the process is necessary and advantageous.

#### 4. Conclusions

We conducted laboratory experiments on the efficiency of three different coordination procedures with 64 students of finance at the University of Kiel in February 1982. In this paper we focus on the contrast between CP1 - the coordination within a conference - and CP 3 - the coordination by means of a decomposition algorithm. Basically, CP3 performs better than CP1 as regards the quantitative results. It has, however, shortcomings on the motivational side, which is one dimension in our concept for measuring the efficiency of alternate coordination procedures.

The results discussed above suggest that further effort should be devoted to integrating people into the decomposition-based coordination as much as possible. This promises to pay off not only in an improved motivation but also in an improvement in the "technical results", i.e. the benefit-cost relation.

The results with CP2<sup>1)</sup>, the coordination by man and machine (decomposition algorithm) strongly indicate: By integrating the managers, near-optimum solutions can be achieved in fewer iterations. Additionally, the level of decision-making autonomy has been perceived to come closer to that in the coordination within a conference. As regards methodology, laboratory experiments on the combination of man and machine in decision-making have proved to be a useful device of research in empirical decision theory.

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1) The principle and the results will be presented by Reinhold Leichtfuß at the 1982-meeting of the Deutsche Gesellschaft für Operations Research (DGOR) in Frankfurt.

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