

OPTIMAL DUCT SYSTEM DESIGN

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1. INTRODUCTION

In an earlier publication [1] optimal transportation of air from one point to another was studied. A few remarks were made about the approach of optimal branched duct design. To introduce the problem of how to design an optimal duct network we want to begin with referring to Fig. 1. This Figure gives a possible lay-out of a duct system for the ventilating or air conditioning of a small-width office building. In Fig. 2 some alternatives are put together. What system will give lowest annual cost? Is it possible to find another alternative which gives lower annual total cost?

How to design a duct system for a large-width building? (Fig. 3). Is it advisable to choose one central system, or is it better to apply more systems? And how to subdivide the building (Fig. 4): should one choose square blocks, or rectangular blocks, or choose a unit per floor?

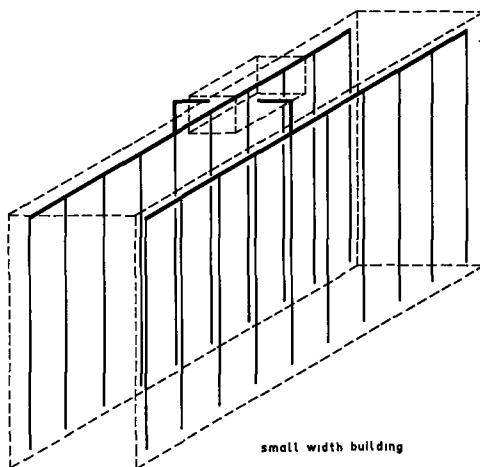
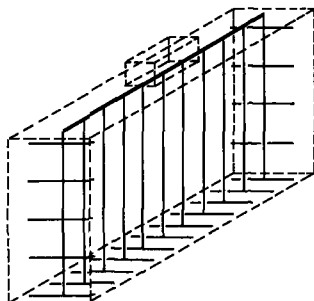


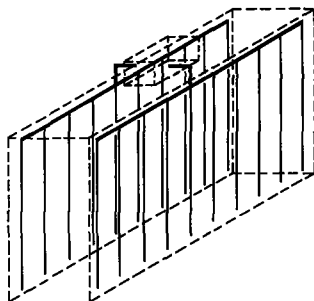
Fig. 1

Fig. 2

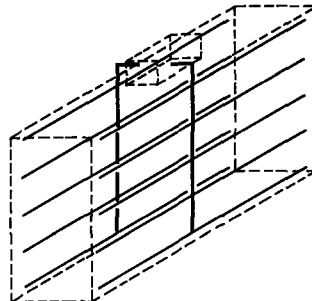
MAIN DUCT (S)



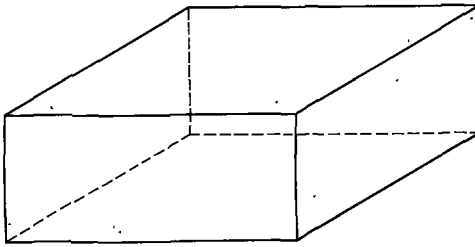
in centre of building ?



horizontal ?

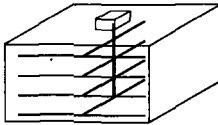


vertical ?

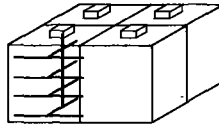


large-width building

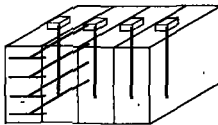
Fig. 3



central air supply ?



or square blocks ?



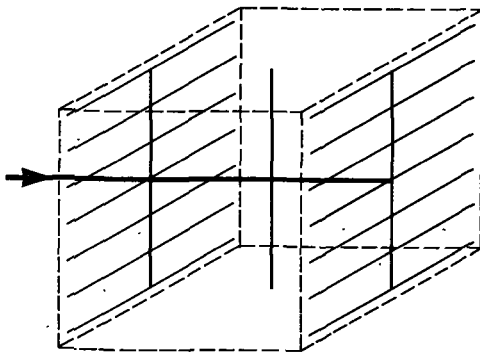
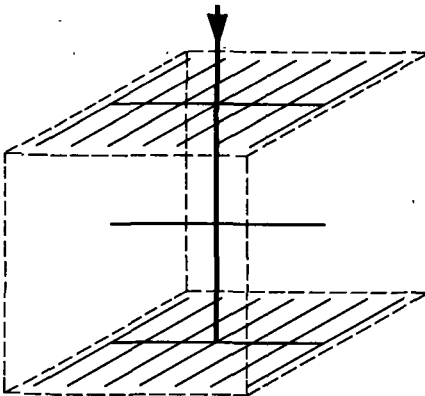
or rectangular blocks ?



or subdividing per floor ?

Fig. 4

Fig. 5



always combinations of flat networks

We want to mention the excellent and extensive study of Swain et al. [2] considering different duct systems. But this study was restricted to alternative duct systems for one certain office building, and no attempt was made to generalize results by making cost data dimensionless. In our search for an optimal duct system we first restrict ourselves to duct systems, ignoring considerations as building construction, air conditioning systems, etc.

If we know the cost consequences of duct alternatives then we can still choose the best solution to fit the air conditioning considerations such as the type of induction unit system, compensation for moving shadows, zoning, etc.

Most duct systems, such as those in Fig. 5, are combinations of flat networks. And networks can be split down to combinations of branched ducts, Fig. 6.

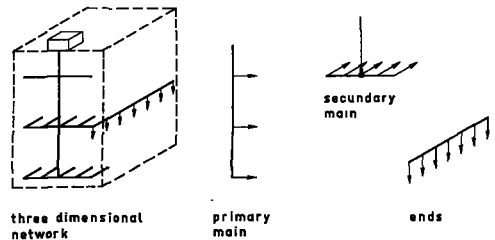


Fig. 6

2. OPTIMIZED BRANCHED DUCTS

Total annual cost of a duct for transport of a certain volume of air from one point to another is a sum of four different cost items:

- power
- duct
- space, and
- heat (or cold) loss.

When we choose a certain velocity, all four cost items can be calculated as follows.

When the velocity is chosen, the cross sectional area is known and the resis-

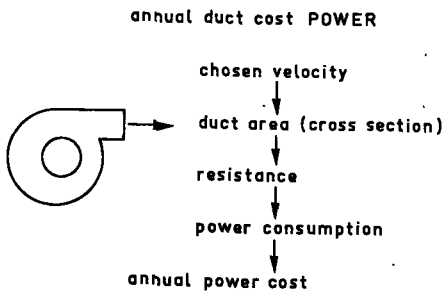


Fig. 7

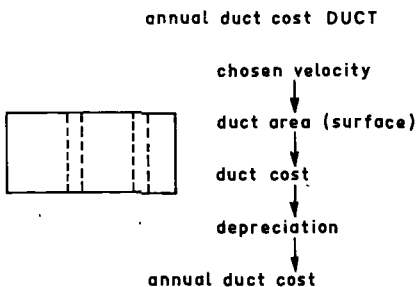


Fig. 8

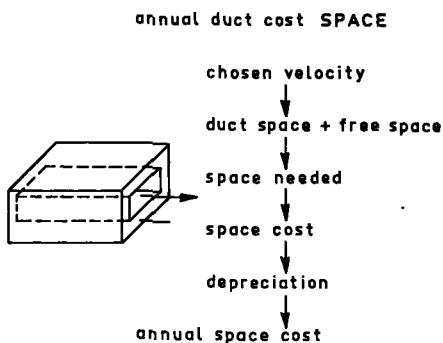


Fig. 9

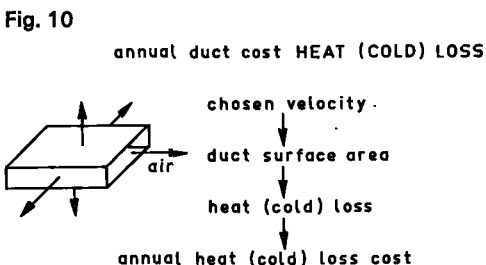


Fig. 10

tance, the power consumed and the annual power cost can be calculated. See Fig. 7.

When the aspect ratio of the cross section is known, the circumference of the duct is known, and so are the duct surface, the cost and the annual duct cost. See Fig. 8. If free space needed around the duct is known, the total space needed is known, and so space cost can be calculated. See Fig. 9. If the ducts do not take away useful space, the space cost has to be neglected.

The air velocity, the circumferential duct surface and the insulation give the heat or cold loss and accordingly the annual cost for loss of heat or cold. Fig. 10.

If the heat lost by the duct is not to be considered as lost for the building, than cost of heat loss must be omitted.

For every velocity one can calculate total cost. Fig. 11. Minimum total cost can be found by varying the chosen velocity, minimizing total cost by iteration. In [1] it was demonstrated already that branched ducts cannot be optimized by optimizing the sections individually.

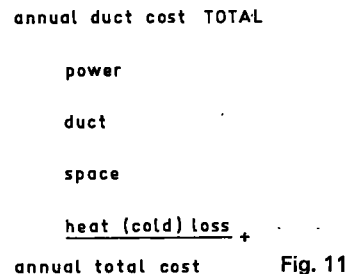


Fig. 11

In designing a branched duct it is common practice to choose one of two calculation methods:

- the constant pressure drop method, or
- the static regain method.

First we consider the results of calculations for branched ducts. We neglected the costs for space and heat loss. Further we assumed equal air supplies for all the branches, spaced at equal distances. The calculations were based on the parameter values shown in Fig. 12.

STUDIES MADE

duct cost dutch	f 50.- /m ²
space cost	nil
energy cost	f 0.05 /kWh
fan efficiency	0.75
running hours	8760 h/a
depr. ducts	0.14 /a
duct diameter	free
λ duct (at $Re = 5 \cdot 10^5$)	0.020
air per branch	0.1 m ³ /s
branches at	3.0 m
modul	3.0 m
floor height	3.0 m

Fig. 12

optimal velocities in m/s along branched ducts
ca constant resistance method

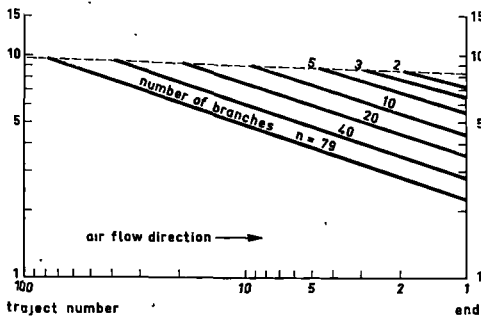


Fig. 13

By looking at the applied parameter values we see that the choice of the diameter is left free. In practice only a limited number of diameter values will be available. But by introducing a limited number of possible diameters in these studies it will hardly be possible any more to find tendencies in the change of optimum annual total cost at changing parameter values. So if we want to find *general*

tendencies we have to accept the possibility of free choice of diameter.

In Fig. 13 the results are shown for ducts with 2, 3, 5, 10, 20, 40 and 79 branches; the calculations are based on constant pressure drop.

We see that the entry velocity should be slightly raised when the number of branches increases.

Further we see that the end velocity has to be lower when the number of branches is higher, and accordingly the branched duct is longer.

When the static regain method is applied, minimum total cost leads to velocity distributions along the ducts, see Fig. 14.

Comparing the results of the constant resistance method with those of the static regain method, one will observe that for application of the latter method the entry velocity has to be chosen higher with an increasing number of branches, and the end velocity has to be lower.

When comparing this Fig. 14 with Fig. 13 we see a large difference in velocity

optimal velocity in m/s along branched ducts
„static regain“ method

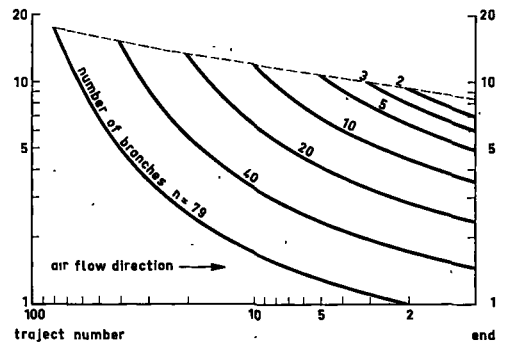
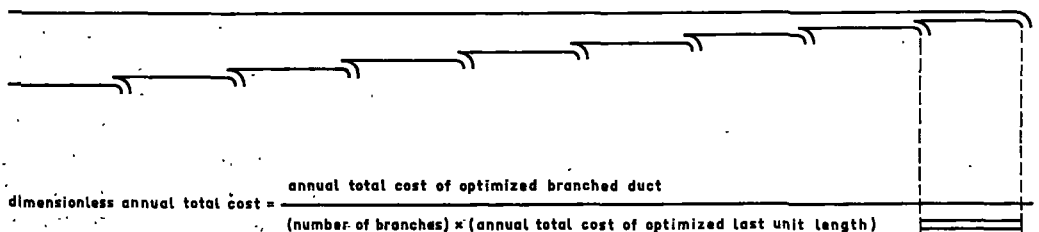


Fig. 14

Fig. 15



levels. But still we found only a small difference in annual total cost.

Annual total cost of an optimized branched duct can be compared with the cost of the optimum duct for transporting the air stream in the last section along a distance equal to the length of that last section of the branched duct. See Fig. 15. Comparison of numerous results of calculations reveals that the ratio of annual total cost of the branched duct to the annual total cost of the last section optimized individually, is largely independent of parameter values.

So it is possible to speak of the 'dimensionless annual total cost of a branched duct averaged per branch'.

In the following we shorten this mouthful of words to 'dimensionless annual total cost' which always means this cost *averaged per branch*.

Optimum dimensionless annual total cost is given in Fig. 16. We see that up to about 20 branches there is only some little difference caused by application of either of the two design methods.

It is also interesting to note that dimensionless duct cost of branched ducts designed at one certain *fixed* velocity, omitting the energy consumed, gives the lower line in the diagram.

At first sight it seems intolerable to work with results of calculations which neglect energy cost, include only the duct cost, and are obtained at always the same fixed velocity. But Fig. 16 shows that the difference between the results obtained with the 'wrong' method of fixed velocity, and the results obtained by the exact iteration method is far from dramatic. The calculation following the 'wrong' method is far faster and cheaper than the exact method. So the simple method was chosen to get a first insight in the tendencies which can be expected.

And in fact the data obtained are fairly close to the results of exact iterative calculation methods based on either the constant pressure drop or static regain concept.

Now we will see how some cost items

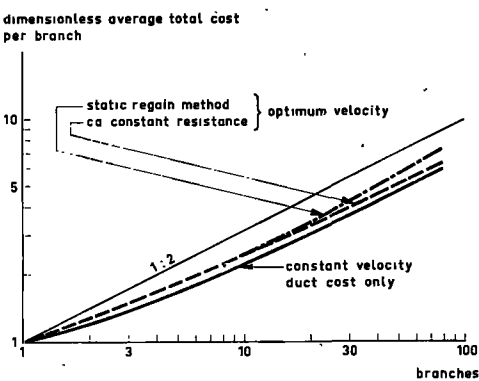


Fig. 16

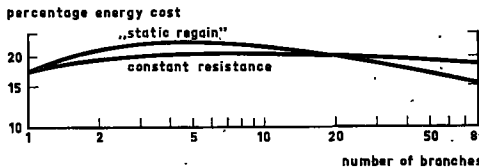
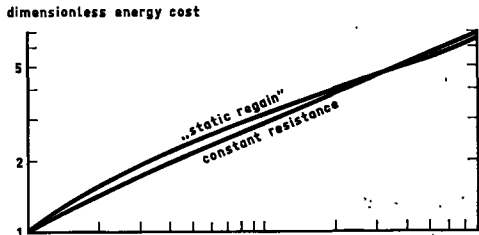
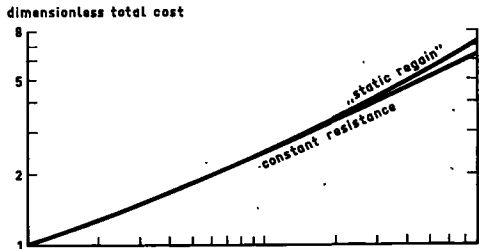


Fig. 17

vary with the number of branches. In Fig. 17, the exact dimensionless annual total cost is given in the upper part of the diagram. But it is also possible to give the dimensionless annual *energy* cost of branched ducts. These are given in the middle of the diagram. We see that, generally speaking, the absolute level of annual energy cost is slightly higher for

designs based on the static regain method.

At more than 30 branches the annual energy is less at the static regain design. But a number of 30 branches is already quite a lot: at a section length of 3 metres the branched duct is 90 metres long!

In the lower part of the diagram it can be seen that annual energy cost is 15 to 23% of annual total cost.

Up to about 20 branches, the static regain method gives a somewhat higher percentage of energy consumption than does the constant pressure drop design.

The pressure needed at the entry of optimized branched ducts increases only slightly with the number of branches. The pressure, p , increases according to the relation:

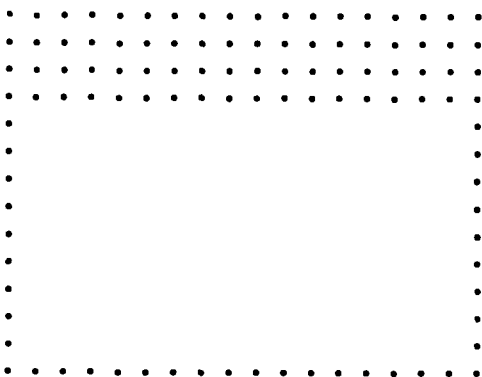
$$p \div (\text{number of branches})^{0.44}$$

3. OPTIMIZED RECTANGULAR DUCT NETWORKS

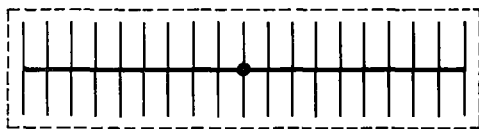
We have found little systematic information about the annual total cost of optimized networks of different sizes and aspect ratios, fed from different situations of the main supply point.

The problem we studied was: what is the best system to supply equal quantities of air to a number of points lying on a square network. Fig. 18. The duct systems studied consisted of one main duct

Fig. 18



how to bring air to the points of a square network ?



what total cost difference ?

Fig. 19

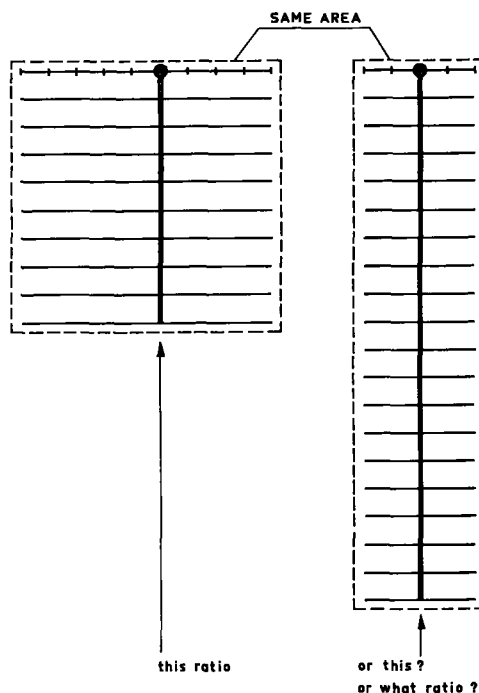


Fig. 20

feeding one type of branched ducts, see Fig. 19.

It is interesting to know what is the difference in annual total cost of the two systems in Fig. 19: the main duct parallel either to the long or to the short side of the field.

What aspect ratio of the field is giving lowest cost: long and narrow fields or nearly square fields? Fig. 20.

And how is total annual cost affected by

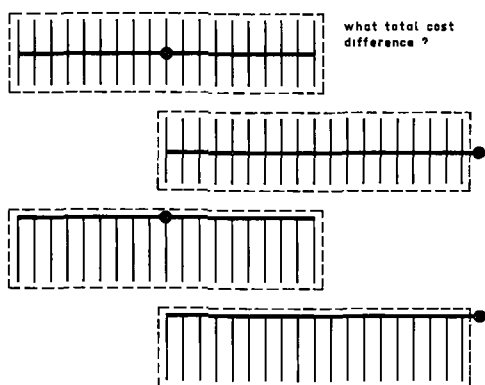


Fig. 21

DTC = dimensionless average annual total cost per branch

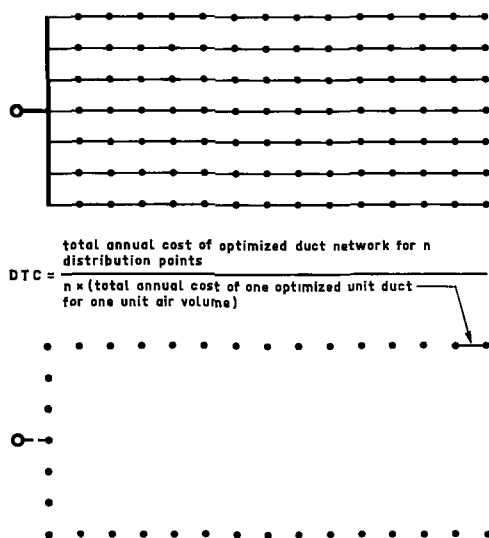


Fig. 22

the choice of the point of supply to the network? Fig. 21.

By studying the results of many optimized rectangular networks it turned out to be possible to define the dimensionless annual total cost per branch in the same way as was done with the branched ducts. See Fig. 22.

We calculated the costs with application of the simplified (constant velocity) method. We made some correction for pressure inequality.

A few duct systems were optimized by the exact calculation method. Comparing results from the simplified and exact

calculation methods we found differences in the order of 5 to 10%. Tendencies remained practically unaltered.

After this control we used the simplified method to calculate the dimensionless annual total cost figures of duct networks varying the following parameters:

- situation of main supply point: 4 situations
- area of the field: 960, 240, 60 and 15 squares
- aspect ratio of the field: all the aspect ratios possible between 0.15 and 6.67 but no branched duct longer than 80 branches.

The results are given in the diagrams Figs. 23 to 26. We see that annual cost of optimized networks is minimum at an aspect ratio somewhat lower than unity, the main duct parallel to the long side giving the lower cost.

The larger the field, i.e. the larger the number of unit squares, the higher the cost per branch.

The larger the field, the lower the aspect ratio should be chosen for minimum total cost.

Further we see to what extent total cost is affected by different situations of the main supply point of the network. See Figures 23/26.

To demonstrate the possible use of the graphs, we compared a few possible air distribution systems for an office building given in Fig. 27.

Dimensionless annual total cost for each of the systems can be found from the graphs directly or by interpolation. Fig. 28. The only configuration giving some difficulties is configuration E (and F). Here we must keep in mind that the central main duct network has to handle twice as much air as the networks lying in the façades.

But per distribution point of this network two points in the façade are supplied by air. So finally the cost of the central network per supply point in the façade is $(\sqrt{2}/2)$ times the cost of a network of equal lay-out for one façade. The cost for the transport from the center of the build-

dimensionless annual total cost

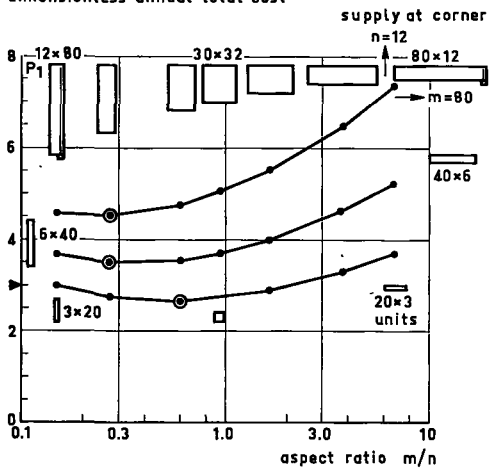


Fig. 23

dimensionless annual total cost

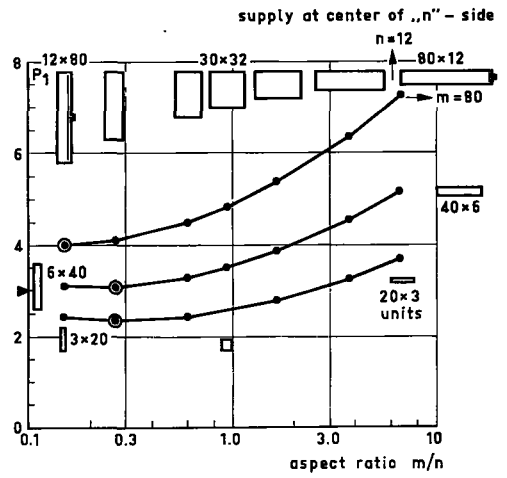
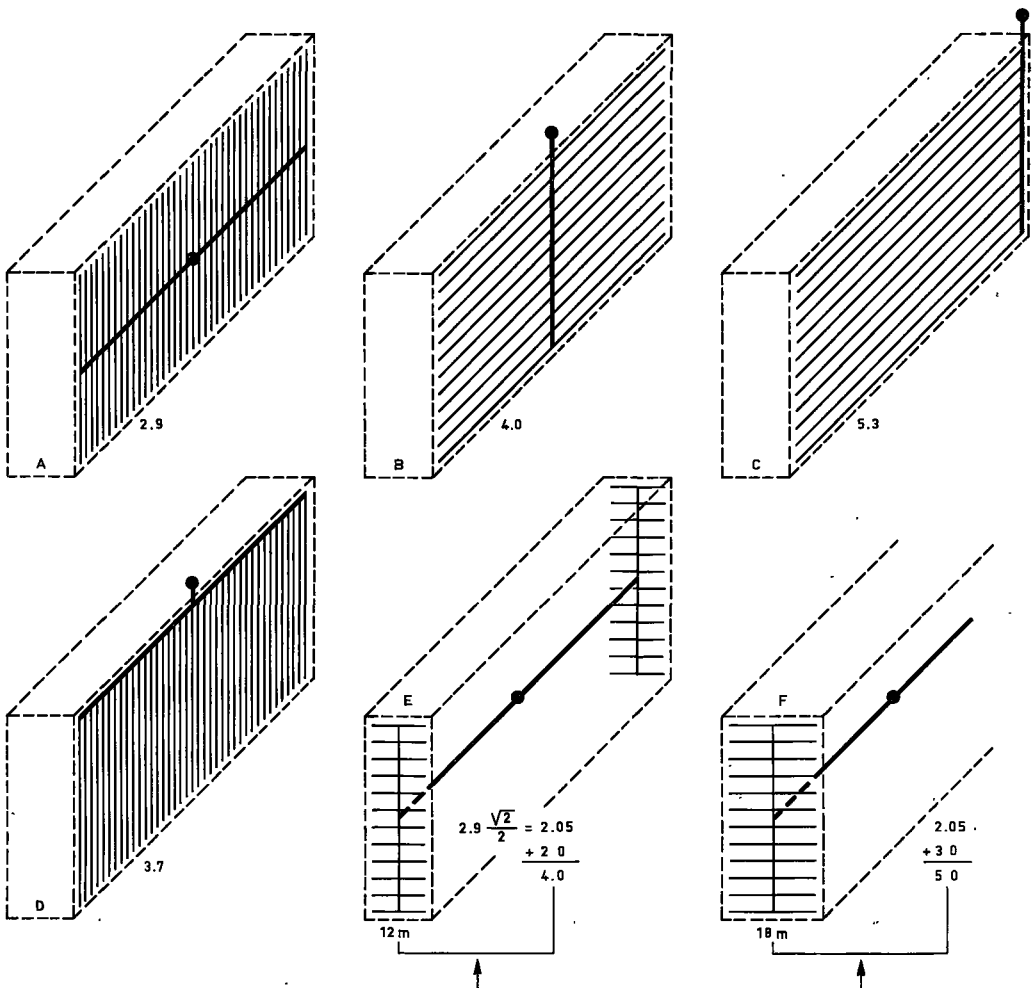
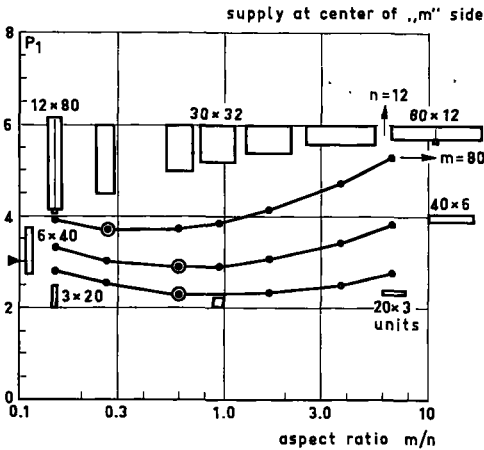


Fig. 24

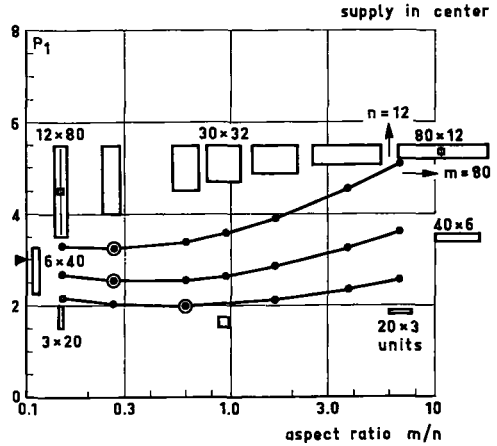
Fig. 28



dimensionless annual total cost



dimensionless annual total cost



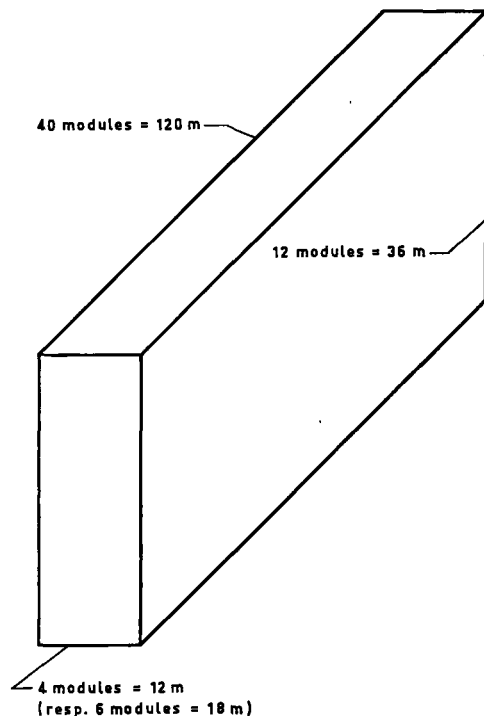
ing to the façade has to be added! This transport is obtained by two unit length unit air transport sections by definition each having a dimensionless annual total cost of unity. So for alternative *E* dimensionless annual total cost per branch will be $2.05 + 2.0 \approx 4.0$. By increasing the width of the building to 3 modules (alternative *F*), the dimensionless annual total cost will increase to $2.05 + 3.0 \approx 5.0$. Considering the first five cost data, we see that costs differ almost a factor of 2. Without systematical knowledge of the kind given in this paper it will be difficult to forecast the cheapest design and to give indications about the relative cost levels of different designs. With the aid of graphs of the kind given one does not need more than a pencil, the margin of a newspaper and a few minutes of time.

4 CONCLUSION

Some conclusions of the studies are:

- ~ It is possible to compare different optimized duct system designs by comparing the dimensionless annual total cost numbers.
- ~ The dimensionless annual total costs of optimized duct systems are largely

Fig. 27



- independent of parameter values and so can be used in different countries without knowing much of the specific local price situations.
- Larger fields cost more per supply point than smaller fields of the same aspect ratio.
 - Annual total cost of optimized branched ducts increases almost with the square root of the air supply per branch.
 - For lowest annual total cost, the main duct should be chosen parallel to the long side of the field.
 - The optimal aspect ratio is not unity (square) and differs more from unity when the number of supply points is larger.
 - Energy cost of optimized branched ducts or duct networks is about 17 to 23% of total cost.
- Comparing the constant pressure drop method with the static regain method, one finds that the latter implies slightly higher annual cost and a slightly higher energy to total cost ratio.

5 REFERENCES

- [1] Bouwman, H. B. – Optimum duct system design, presented at the Rehva Conference, CLIMA 2000, held at Milan, March 1975.
- [2] Swain, C. P. et al. – The choice of air conditioning systems J.I.H.V.E. **32** (1964) No. 4, Apr., 1–41, No. 11, Nov., 307–320.

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