# A MODEL FOR THE ANALYSIS AND DESIGN OF DISTRIBUTED INFORMATION SYSTEMS

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## Abstract

Development of teleinformatics imposes to analyze, reconstruct information systems of total organizational systems. Exact modelling is indispensable in analytic and design work. The presented model involving the element structure of the information system, the internal structure of the elements and of their relations, helps analysis, evaluation and design of information storage and transfer, sign storage and transfer, as well as of algorithms and operation needed for information processing, in a conform and consistent system, taking also time cycles into consideration.

## Introduction

Accelerated development of systems theory, of systems engineering, as well as of computer engineering permits to attempt analysis and development of ever increasing systems, in agreement with various integration phenomena and endeavours in technics, economy, and in social domains. As examples, the problem of designing internal structures of complex products (computers), cooperation for producing various items, planning of labour division or cooperation between parent company and affiliated firms, planning components and relations of internal organizations, disclosure and analysis of human relations within the society, integrated development of whole organisms, etc., can be mentioned.

Integrative endeavours increasingly impose research and development of sufficiently exact method and means. In this field, computerization has brought about several achievements, and the implementation ever widens. Still, an analytic system model has to be found such as to suit systems analysis and development, even without a computer. Certain initial attempts have been known and published in this field [1, 2, 7]. After several years of research work, a rather flexible, hierarchic analytic systems model could be developed and applied, in course of analyzing complex enterpreneurial information systems. In the following, this model will be presented to the depth possible in the given frames, completed by references for further deepening relevant knowledge.

## General fundamentals of systems analysis and development

In analyzing or developing systems, it is essential to describe them, starting from their structure, where general application of the system concept is indispensable. As concerns generally valid definitions of a "system" starting from that by Bertalanffy, the concept of system has the invariable characteristics

— to consist of elements; and that
— these elements are interrelated [3, 5].

Relations between the elements are actual functions of tasks prescribed for the system. Thereby, a general analytic system model has to suit flexible description of the elements and their relations. Obviously, elements have to be somehow conveniently arranged in the selected model. The general utility requirement of the model seems to counteract it. According to practical observations made in the analysis of various systems, their inherent elements are arranged somehow superposed or juxtaposed. In other words, elements within a system are arranged according to a certain hierarchy [1, 4]. This consideration was underlying Packard's so-called information pyramid for control information systems, generalized as a fundamental to be started from [4, 8].

## Development of the spatial geometric system model by Packard into an alphanumeric, analytic model

Within the Packard's information system pyramid, superordinate or subordinate managing levels are definible. At any management level a number of elements are operating to perform management tasks (information storage, processing, decision, etc.). In fact, these elements — persons, sections, offices, etc., as the case may be — are numbered according to some order of perambulation.

Let control levels be denoted by $1, 2, \ldots, n$ as the second subscript, and elements situated at each control level as indicated above, by $1, 2, \ldots, m$, as first subscript. Of course, to exactly distinguish elements, also the level accommodating the element has to be indicated by a subscript. This is the most perspicuous for subscript $m$ denoting last element of each level, affected therefore with another subscript for the control level. Those outlined above permit to construct a hierarchic, perfectly general, analytic element structure model, best illustrated in a coordinate system according to Fig. 1. This system of notations is seen to be perfectly general by permitting to denote arrangement of an arbitrary number of control levels. In case of this in-plane model, Packard's pyramid may be fixed by stipulating inequality

$$m_1 > m_2 > m_3 > \ldots > m_n. \quad (1)$$

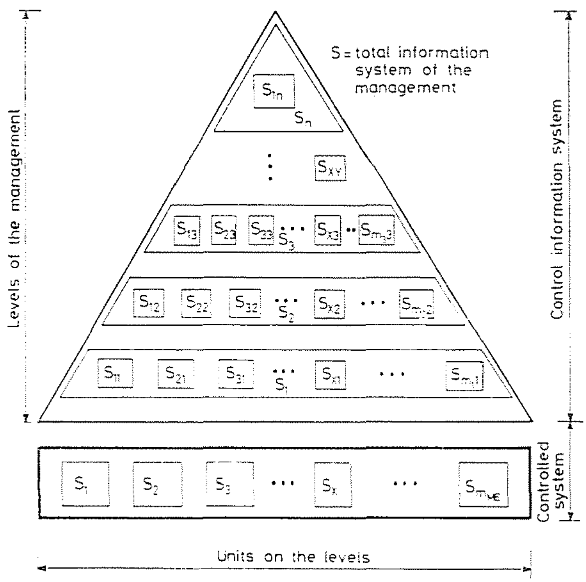


*Fig. 1.* General element structure in a hierarchic control system

This notation of elements and levels can be applied to create system structure indices permitting organometric measurements, too.

If e.g.:

$$\frac{m_1}{m_2} = \frac{m_2}{m_3} = \frac{m_3}{m_4} = \ldots = \frac{m_{n-1}}{m_n} \tag{2}$$

there is *a system of linear hierarchy.*

For:

$$\frac{m_1}{m_2} < \frac{m_2}{m_3} < \frac{m_3}{m_4} < \ldots < \frac{m_{n-1}}{m_n} \tag{3}$$

there is *a system of degressive hierarchy.*

$$\frac{m_1}{m_2} > \frac{m_2}{m_3} > \frac{m_3}{m_4} > \ldots > \frac{m_{n-1}}{m_n} \tag{4}$$

there is *a system of degressive hierarchy.*

If proportions between element numbers at each level, passing from below upwards, contain several of the indicated cases, there is *a system of mixed hierarchy.*

In deepening the structure of this hierarchic system model, categories in Fig. 2 have to be modelled with a general validity. That is, static and dynamic structure, element structure, internal structure of elements and structure of the relation between elements have all to be imaged by quite generally applicable model structures.

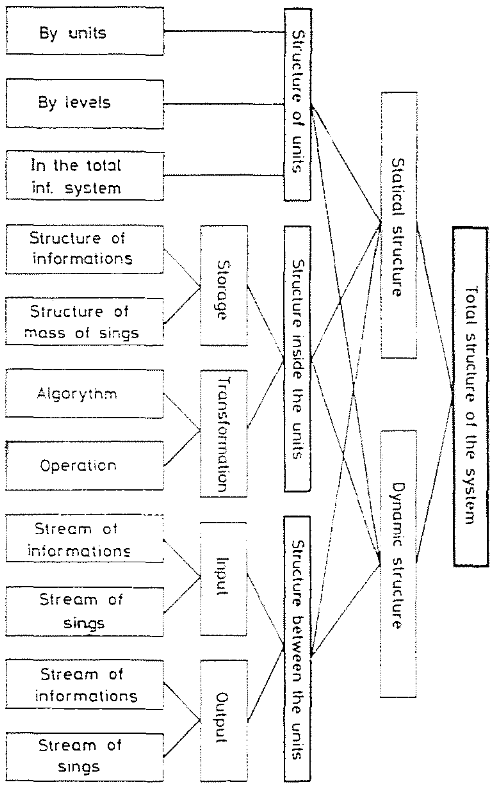


*Fig. 2.* Survey of domains of modelling information system structures

## Analytic, static and dynamic modelling of element structures

Striving to completeness according to Fig. 1, the element structure may be modelled element-wise, control level-wise, or globally in the entire system. In-plane situation of an element may be indicated with two coordinates. It is sufficient to indicate a control level along the vertical axis. While for the entire system no coordinate is needed. Since elements and levels belong to the entire system, their notation will keep symbol "$S$", joined by the mentioned identifiers as subscripts. Thereby

— a general element may be denoted $Sxy$
— a general level may be denoted $Sy$ (5)
— the entire system may be denoted $S$.

Static model equation of elements possible at an arbitrary level $y$:

$$S_y = \{S_{1y}, S_{2y}, S_{3y}, \ldots, S_{my}\} = \bigcup_{i=1}^{i=m_y} S_{iy} \,. \tag{6}$$

In this notation, elements of different subscripts are considered as different ones.

Model equation of elements occurring in the entire system may be given in terms of level-wise elements, by summing Eqs. (6):

$$S = S_1, S_2, S_3, \ldots, S_n = \bigcup_{j=1}^{j=n} S_j = \bigcup_{i=1}^{i=m_y} \bigcup_{j=1}^{j=n} S_{ij}. \tag{7}$$

Since

$$i \leq \infty \text{ and } j \leq \infty \text{ and integer,} \tag{8}$$

the outlined element model may be considered as of fully general validity, and its use is not restricted either for large or for small systems.

In analysing a concrete system, some elements may fall out. This is no difficulty in modelling, namely, these terms will be considered as zero. This is exemplified by the dynamic modelling of the element structure where elements do not function in every time cycle. The dynamic modelling of the element structure has to start from the fact that organizations perform control tasks intermittently rather than continuously. Thereby minute, hourly, daily, weekly, monthly, yearly, etc. operation cycles have to be distinguished. Let cycle times be denoted by Roman numerals (I, II, III, . . . ,) in increasing order. Applying these notations at the top left corner of main symbol "*S*" of the element, to the sense, indicates what are those among all the elements of the system that function in given time cycles. That is, taking the complete structure in Fig. 1 as many times as there are cycle times to be distinguished, certain elements (inoperating in the given cycle) will be zero in the single element structure denoted by the same Roman numeral. Choosing an arbitrarily short cycle time, the discrete timeliness of the model may be made theoretically nearly continuous.

## Analytic, static and dynamic modelling of th e internal structure of the elements

Two fundamental statements may be made on the elements of the control information system. On one hand, input information is properly transformed to output information. On the other hand, adapting themselves to the standard cycle time in the control system, they store some information in given codes. Information storage is also needed for defining their operation rules. Thus, modelling of the internal structure of elements may be primarily reduced to modelling of the transformation rule to be realized in them, that is, of the algorithm.

In the case of one element, transformation becomes:

$$_0I_{Sxy} = T_{Sxy}(_iI_{Sxy}), \tag{9}$$

where: $I$ — information;
$o, i$ — output, input;
$T$ — rule of transformation.

Considering the possibility to involve information stored after transformation ($_TI$) into the algorithm, (9) extends to:

$$_oI_{Sxy} = T_{Sxy}(_iI_{Sxy}, _TI_{Sxy}). \tag{10}$$

Since transformation follows some logic or mathematic rule, algorithm, that defining operation of the element may be written as:

$$A_{Sxy} = f(T_{Sxy}). \tag{11}$$

Transformation according to a given *algorithm* requires some *set of operations*, depending, of course, exactly on the kind of algorithm. For transformation made e.g. by a computer, number "O" of operations for one and the same algorithm also depends on the kind of programming ($p$), so that, for one element,

$$O_{Sxy} = f[p, (T_{Sxy})] = f(p, A_{Sxy}). \tag{12}$$

Stored information may be transformed by coding ($c$) to storable signs, hence:

$$_TJ_{Sxy} = f(c, _TI_{Sxy}). \tag{13}$$

All in all, the internal structure of the element has to be modelled as:

— stored information $_TI_{Sxy}$
— stored signs $_TJ_{Sxy}$ (14)
— transformation algorithm $A_{Sxy}$
— operations needed for transformation $O_{Sxy}$.

Using notations in Fig. 1, in modelling the same components within a complete control level, merely subscript "$x$" has to be omitted. While for a model referring to the entire system, symbol "$X$" is the only subscript. Accordingly, at a general control level "$y$", model equation of the stored information becomes:

$$_TI_{Sy} = \{_TI_{S1y}, _TI_{S2y}, _TI_{S3y}, \ldots, _TI_{Sm_yy}\} = \bigcup_{i=1}^{i=m_y} {_TI_{Siy}}. \tag{15}$$

With a view on (13), *stored signs* are expressed by:

$$_TJ_{Sy} = \{_TJ_{S1y}, _TJ_{S2y}, _TJ_{S3y}, \ldots, _TJ_{m_yy}\} = \bigcup_{i=1}^{i=m_y} {_TJ_{Siy}}. \tag{16}$$

The overall algorithm for one control level:

$$A_{Sy} = \{A_{S1y}, A_{S2y}, A_{S3y}, \ldots, A_{Sm_yy}\} = \bigcup_{i=1}^{i=m_y} A_{Siy}. \tag{17}$$

Taking (12) into consideration, the model equation of operations becomes:

$$O_{Sxy} = \{O_{S1y}, O_{S2y}, O_{S3y}, \ldots, O_{Sm_y y}\} = \bigcup_{i=1}^{i=m_y} O_{Siy}. \tag{18}$$

It is of importance especially for designing divided data processing or intelligence systems not to modell internal structures of elements at a given control level but to examine internal structures of elements at all the levels of the entire system, requiring the following relationships:
In case of *stored information:*

$$_T I_S = \{_T I_{S1}, {_T I_{S2}}, {_T I_{S3}}, \ldots, {_T I_{S_n}}\} = \bigcup_{j=1}^{j=n} {_T I_{Sj}} = \bigcup_{i=1}^{i=m_n} \bigcup_{j=1}^{j=n} I_{Sij}. \tag{19}$$

In case of the *needed algorithms:*

$$A_S = \{A_{S_1}, A_{S_2}, A_{S_3}, \ldots, A_{S_n}\} = \bigcup_{j=1}^{j=n} A_{Sj} = \bigcup_{j=1}^{j=m_y} \bigcup_{j=1}^{j=n} A_{Sij}. \tag{20}$$

Concerning the stored signs, taking (13) into consideration, a model conform to (19) may be written. The needed operations are written similar to (20), taking (12) into consideration.

The above offer possibilities for the static modelling of the internal structure of elements. Also here, dynamic modelling relies on affecting storages with different cycle times, and transformation by proper subscripts. For instance, to make model equation (16) time-sensitive, left-hand side of the equation is decomposed as:

$$^t_T J_{Sy} = {^I_T J_{Sy}}, {^{II}_T J_{Sy}}, {^{III}_T J_{Sy}}, \ldots \tag{21}$$

Natural consequence of this decomposition is the same decomposition of every term in the right-hand side of Eq. (16).

In this way, model equations not only for signs but also for stored information, algorithms and operations may be made time sensitive, at the level of compositeness of elements, control levels and the entire system.

In connection with modelling the internal structure of elements, remind that the structure acquainted with can be differentiated according to further viewpoints.

For instance, letter superscripts of symbol for algorithm may refer to the type of algorithm ("M" for mathematical, "P" for data processing, "D" for decision algorithm).

An advantage of the presented model of the internal structure of elements is to permit conform modelling of the stored information, signs and algorithms and operations, in a perfectly identical decomposition, a priori safeguarding the coordinability.

## Analytic, static and dynamic modelling of relations between elements

System complexity increases in proportion to the number of elements and of their interrelations. After Starr [9], the possible number of relations amounts to:

$$R = \frac{E^2 - E}{2} \tag{22}$$

where $E$ — element number within the system.

Relations between elements may have either of two directions, doubling the number of possible interrelations:

$$D = 2\,R = E^2 - E. \tag{23}$$

The quadratic relationship accelerates the growth of the number of possible directions compared to the number of elements, making generally valid modelling of all the relations rather difficult. Therefore in modelling the relations between elements, logical considerations have to be started from.

Practically, general system element $Sxy$ (Fig. 1) may be in either of the following relations:

1. relations to elements of the controlled system, (ME)
2. relations to one or more elements at a lower control level, (B)
3. relations to elements at several lower control levels
4. relation to elements at the same control level, (H)
5. relation to one or more elements at a higher level, (F)
6. relation to elements at several higher levels,
7. relation to an external information system. (e)

Directions distinctible in the listed relations, separated according to input and output for one element, are seen in Fig. 3. In all the enumerated relations, directions may be modelled, separated to input and output. In modelling, however, also the relation purport has to be represented. In case of a control system, this purport means flow of some kind of information. Of course, flow of information involves flow of the carrier signs somehow coded, as shown by (13).

Directions may also be modelled by set equations but for solving practical problems, modelling by directed graphs is superior.

Information flowing in a given direction is best modelled by set equations, namely, there is always an assortment of information.

Flow of signs carrying information is best given in matrix form, since they enter development of the data transfer system.

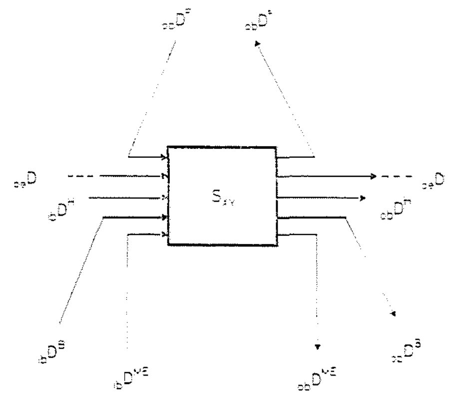

*Fig. 3.* Relations and directions reckoned with for one element

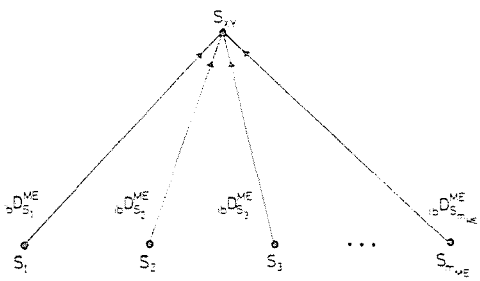

*Fig. 4.* Directed graph modelling of directions

In the actual setting, modelling of the complete flow system cannot be presented even for the complete informational relations of a single element. However, modelling of input relations of one element to all elements of the material-power system will be surveyed, relying of Fig. 4, where elements are indicated by a point each.

In conformity with Fig. 4, model set equations to be written for *information flow directions* (directions in channels corresponding to relations) are:

$$ {}_{ib}D^{ME}_{Sxy} = \{ {}_{ib}D^{ME}_{S_1}, {}_{ib}D^{ME}_{S_2}, {}_{ib}D^{ME}_{S_3}, \ldots, {}_{ib}D^{ME}_{Sm_{ME}} \} = \bigcup_{j=1}^{j=m_{ME}} {}_{ib}D^{ME}_{Sj} \qquad (24) $$

Looking at the figure it is obvious that, in case of a directed graph, it is needless to write model equation (24) since the relations are mapped. But in case of computer analysis or design, modelling by (24) is more advantageous.

Information flowing in each direction is correctly modelled if conformity is safeguarded. To this aim, all subscripts are applied like in Eq. (24), excepted that symbol "D" for direction has to be replaced by "T" for information.

$$ {}_{ib}I^{ME}_{Sxy} = \{{}_{ib}I^{ME}_{S_1}, {}_{ib}I^{ME}_{S_2}, {}_{ib}I^{ME}_{S_3}, \ldots, {}_{ib}I^{ME}_{SmAE}\} = \bigcup_{=m}^{j=m_{ME}} {}_{ib}I^{ME}_{Sj} . \tag{25} $$

Modelling, in addition, *flow of signs carrying* information in each direction, model equations may be written using the same notations but in row matrix form. Then, the main sign will be J.

$$ {}_{ib}J^{ME}_{Sxy} = \{{}_{ib}J^{ME}_{S_1}, {}_{ib}J^{ME}_{S_2}, {}_{ib}J^{ME}_{S_3}, \ldots, {}_{ib}J^{ME}_{SmAE}\} = \bigcup_{j=1}^{j=m_{ME}} {}_{ib}J^{ME}_{Sj} . \tag{26} $$

The three kinds of model equations rather simplify checking up and coordination of coherent terms in analysis and design.

For any of relations 1 to 7 following Eq. (23), the outlined method of applying subscripts may be similarly applied in each of the three modelling scopes.

Assuming relations have been modelled by a directed graph, left-hand sides of all model set equations representing information flow in relations between elements at different complexity levels have been tabulated in Fig. 5, making up 30 set equations. Conform modelling also of directions and information carrier signs in flow requires mapping of a total of 90 model equations in the presented mapping system. In our practice, of course, the complete assortment of these equations has been made use of. Actually, however, only relation of the complete information system to a medium control level, of importance mainly for distributed systems, is presented in Fig. 6.

| Information relations | | Internal (b) | | | | |
|---|---|---|---|---|---|---|
| | | Controlled system | Lower | Horizontal | Higher | External |
| | | | management levels | | | |
| | | ME | B | H | F | e |
| Input (i) | to the $S_{xy}$ units | ${}_{ib}I^{ME}_{S_{xy}}$ | ${}_{ib}I^{B}_{S_{xy}}$ | ${}_{ib}I^{H}_{S_{xy}}$ | ${}_{ib}I^{F}_{S_{xy}}$ | ${}_{ie}I_{S_{xy}}$ |
| | to the $S_y$ level | ${}_{ib}I^{ME}_{S_y}$ | ${}_{ib}I^{B}_{S_y}$ | ${}_{ib}I^{H}_{S_y}$ | ${}_{ib}I^{F}_{S_y}$ | ${}_{ie}I_{S_y}$ |
| | to the total S information system | ${}_{ib}I^{ME}_{S}$ | ${}_{ib}I^{B}_{S}$ | ${}_{ib}I^{H}_{S}$ | ${}_{ib}I^{F}_{S}$ | ${}_{ie}I_{S}$ |
| Output (o) | from the $S_{xy}$ units | ${}_{ob}I^{ME}_{S_{xy}}$ | ${}_{ob}I^{B}_{S_{xy}}$ | ${}_{ob}I^{H}_{S_{xy}}$ | ${}_{ob}I^{F}_{S_{xy}}$ | ${}_{oe}I_{S_{xy}}$ |
| | from the $S_y$ level | ${}_{ob}I^{ME}_{S_y}$ | ${}_{ob}I^{B}_{S_y}$ | ${}_{ob}I^{H}_{S_y}$ | ${}_{ob}I^{F}_{S_y}$ | ${}_{oe}I_{S_y}$ |
| | from the S information system | ${}_{ob}I^{ME}_{S}$ | ${}_{ob}I^{B}_{S}$ | ${}_{ob}I^{H}_{S}$ | ${}_{ob}I^{F}_{S}$ | ${}_{ob}I_{S}$ |

*Fig. 5.* **Left-hand sides of the complete informational relation system model equations**

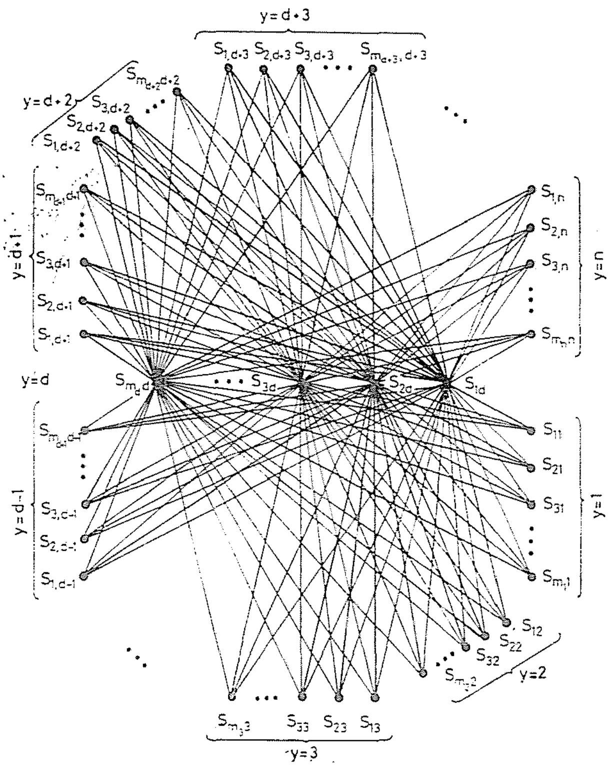

*Fig. 6.* Graph of the relations of elements at an intermediate control level to elements at other levels of the system

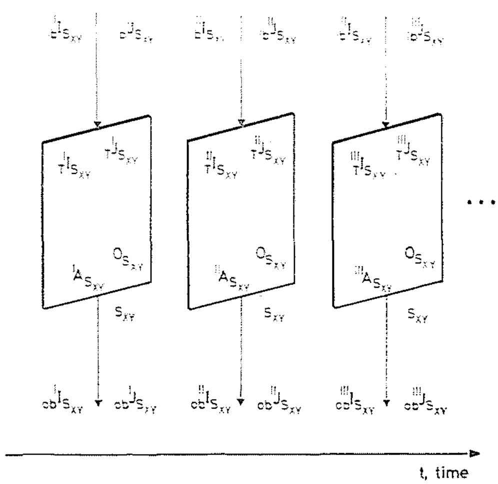


*Fig. 7.* Differentiation with respect to time of all modelled components of a system element

Possibilities of modelling the timeliness of relations in case of a system element are illustrated concisely in Fig. 7, by timely protracting the internal structure of the element. The same procedure may be applied for a complete control level or information system.

## Projection of functional structure on the hierarchic and analytic model, practical application

The presented system model suits to interpret information, signs, algorithms, operation needed for a wide range of control functions of the organization. Of course, it requires certain prealable analytic or design work. In its course, elements, their internal components, and their existing interrelations are placed to the proper level and place as indicated in the model. In case of design, the same is done with the system components. The most exact solution is that where the control chain model is established for every important goal and partial goal and for the required functions, from the function with the longest to that of the shortest operation time cycle.

Control chain model components can be placed in the described analytic model since it permits to insert feedback relations in the modelled relations.

According to experience, the control chain model for an enterprise has to be established from about 15 main control circles in the first design phase. Thereafter the elements, information relations, stored information and algorithms may be accommodated in the model, taking control levels into consideration. Thereby the analytic general model becomes a control system model able to provide for functions of the organization. The thereby actualized system model is of great help in designing decentralized, hierarchic systems with a computer network, indicating also spatial delimitations in the otlined model.

The presented modelling method is, according to our experience, rather efficient for the analysis and design of spatially extended and rather complex traffic control systems.

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