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Mathematical background of key performance indicators for organizational structures in construction and real estate management

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Abstract

Construction projects as well as comprehensive projects of Real Estate Development are evolving more and more as a matter of complex interacting networks driven by means of coordination and motivation. Profound analysis of networks is done since several years with remarkable success in particular by sociologists. By modelling social networks through methods provided by Linear Algebra and matrix calculation, some interesting general parameters can be formulated, which characterize the networks solely based on its structure. Social networks are developing on the background of personalities and their interaction specified by sociology in general and in particular by a subset of interaction means given by e.g. software restrictions on respective platforms. Such procedures turn out to be directly applicable to networks formed by participants in construction projects like trades, subcontractors, workers, departments, hierarchical groups and other involved parties. The generalized personalities are also defined by their tasks and their according interests and motivation, where the interaction is given by legal dependencies and contracts. Not much diverse from this situation are the markets in real estate development, where players and rules are given accordingly. In this research we propose to define network parameters for project interaction structures in construction as well as in development situations based on Linear Algebra and analyze these for the a priori elaboration of well supported interaction schemes. Furthermore already existing parameters are to be identified and mapped on this parallel world in order to improve the understanding and thus the definition of an organization plan as an inevitably required precondition for well prepared projects.
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1. Introduction

Recent progress in Project Management reveals that projects are becoming more and more large and complex. Increasing magnitude leads to the inevitable fact, that they can no more be held and overseen by one hand. As they tend to develop complexity which is a high degree of interaction between the numerous aspects somebody or some unit is required to handle the whole system and be held responsible. Yet high complexity also includes high specifity of the singular aspects as well as of the task of coordinating these and thus implies the need of a variety of very specialized knowledge which is usually not commonly available. Furthermore as projects are defined as being unique and nonrecurring high skills of execution are precondition to success in order to do things right from the beginning because there is no possibility to redo them without considerable consequences.

The classical solution to this situation is division of work [30] awarding subtasks to respective specialists. This solves the demand for skills but induces the new requirement of motivation and coordination. Second parties need to be encouraged to share the primary goal, to want to do their best and to cooperate on the cost of reduced overall profit (Principal Agent Problem). Secondly as the main task becomes divided into pieces, interfaces need to be defined and information to be transferred to give the executive units the best possible means to carry out the respective segment still fitting into the overall context. This is commonly summarized as expense of coordination.

Therewith complex strongly interacting projects are mapped on networks of primarily independent players which are connected by contracts determining aspects of motivation – remuneration and other incentives – as well as coordination – information, design and plans.

On this background efficiently and successfully completing a project comes down to be a matter of risk management [41][43]. Traditionally projects are subject to risky issues in terms of circumstances and variables which cannot be predicted absolutely and therefore need to be dealt with by understanding probabilities, possible hazard and the implementation of appropriate control-mechanisms. Conducting more complex projects thus extends such approaches to a view on the uncertainties of the network structure itself and the connecting ties. The connections are formed by contracts and therewith suffer principally from incompleteness. Lack of perfectness ranges from the description of tasks, properties and required results in quality, time and consumption of resources to the uncertainty of the efficiency of the implemented incentives.

This raises the question of the role of the network itself and of whether stability can be obtained by constructing secure and flexible, probably self-repairing or at least failure tolerant network-structures ensuring a positive result.

2. Networks

2.1. Networks in Construction and Real Estate Management

Network structures in conducting projects in Construction or in Real Estate Management mostly comprise different interaction classes and contents at the same time and thus form a set of multiple interleaving structures. E.g. elements would possibly be single persons or groups of persons, departments, companies, authorities and administrations. Fairly different elements would be given by activities, work packages and tasks which would produce results but require pre-products and resources, possibly sharing them. Finally elements might be the mentioned products, pre-products, resources and information which are prepared and developed by activities. As numerous in type and character the elements are, as multiple are their possible interactions which need to be modeled.

Thus conducting large projects and successfully completing them is first of all solidly based on the assumption of specialists and methods capable to fulfill the requirements of the single tasks. Evidently this is true as all smaller projects are based on this. Under this precondition large projects focus on the singular challenge to find and combine them by coordination and motivation and make them accomplish the task and furthermore form the network to encourage or force them to do so successfully and efficiently.

This implies the careful analysis of each singular element and the local interaction with its direct neighbors. Secondly the network itself needs to be analyzed respectively designed and formed providing the overall partial and total developments and results as emergent values. This is to make the local elements work not only targeted but efficiently and safely. On this background the network needs finally to be optimized according to Malik and Wiener [26][25][39] which can only be accomplished by controlling and steering the flow of information i.e. by designing the contracts that form the network.

Traditionally relevant networks are in a first approach built by the use of the classical work break down structures (e.g. [20][24][33][34]). The project task is broken down along a graph theoretical tree-structure finally to work packages. Since a tree-structure can only follow one singular characteristic WBS are constructed vertically distributing and assigning responsibility. Thus elements are tasks and subtasks, often correlated with products and sub-products created within the tasks and consumed resources. Finally work packages are leading to activities as the lowest level of the tree. Corresponding to the exclusively vertical tree-structure all horizontal interactivity is so far neglected for the purpose of unambiguity. Further interrelations are only introduced at the very bottom level of the activities where classical networks structures allow for time and resource related interactions. These are according to theory of graphs only restricted to the existence of a starting node, an ending node and most of all to being loop-less which is a very artificial requirement, never matching reality. Nevertheless the restrictive network of strong preconditions and post-conditions of production activities can be modeled only here.

2.2. Social Networks

The social and behavioral science has shown considerable interest in investigating networks during the last decades (e.g. [38]). In recent times a new type of huge social networks has come up as a fairly new phenomenon and has been studied widely. These are implemented on computer networks for easy access and model social interactions of participants based on their free decisions to share personal information and interest. Therewith structures are formed which are subject to no predefined graph-theoretical rules but on purely object-related short-path communication. They are not purposefully modelled from outside, yet, model themselves with respect to a general purpose of forming communities within higher order communities and thus serving a higher unspoken goal driven by local motivation. So to say, structures are formed to perform some sort of a common task, thus creating and optimizing itself, probably also terminating itself if no longer matching or just losing the commons interest. The software behind social networks only provides the means of interaction i.e. the definition of dependence and allows the participants to form the network appropriately.

The constructional counterpart to this is the installation of project platforms offering to conduct large projects where a number of participants share a goal and all the interfacing information. These are well established in Construction and Real Estate projects. In contrast to purely social networks the project managers try to handle the interaction on such platform very restrictively and channel the required information and communication along well defined networks paths in order to keep the structure efficient and targeted. Typical applications are given by modeling business processes very accurately in order to force participants to follow predefined structures, which are possibly optimized, in some cases less. Yet again only the means of communication are provided, the motivation to share the goal is determined by the underlying contracts. Therefore, designing structures is merely a matter of to which extent hierarchical vertical structures were to be replaced by horizontal self-organizing structures.

On any account as division of work leads to coordination and motivation demands they are modeled by the definition of interaction which is comparable to the efficiency automatisms found in social networks. This raises the question of how to define specific means and degree of interaction to make a network function and lead to a predefined result. Furthermore measurement parameters need to be found to judge the efficiency and safety of a predefined or to some degree self-developing network. Therefore a thorough analysis of the network key parameters is expected to reveal typical characteristics of project structures as well as of social networks.

3. Matrix calculus

3.1. Cross-Impact Approach

Operability and predictability of networks has been elaborated under the notification of the Cross-Impact approach ([17][18]) and to some extent used and modified as the Sensitivity Modell [37]. Basically the impact of a number of aspects or variables (equating network nodes or participants) on each other is denoted as probability estimation [0..1], later in a more qualitative view as strength ranging from 0 to 3 (none to strong impact) and listed on a square matrix where each participant is assigned a row as well as a column. The horizontal sum of elements for each row is named the active sum AS and represents the activity role of a participant indicating of how actively its influence on all other network members would be. Simultaneously the vertical sum throughout a column yields the passive sum PS , indicating the degree of reactivity of the respective member to all other players. The combination of these two values allows characterizing the criticality $P=AS{\cdot}PS$ of a node. If active-sum and passive-sum both are large small modifications would lead to significant positive feedback effects which likely destabilize a closely coupled system. On the other hand both parameters being low stand for participants ready to stabilize a system by damping modifications. The ratio $Q=AS/PS$ denotes the parameter of control ranging from actively in control of the system if high to reactive on the low side if strongly responding to modifications.

This very plain linear model mirrors in no way more complex structures but may serve as a fairly well established starting point in analysis and design of strong structures.

3.2. Adjacency Matrix

The common approach starts with modelling all participants on a network as nodes on a graph (sociogram) and all interactions as edges [38]. In order to access graphs by mathematical means they need to be denoted as matrices (sociomatrix). In an unweighted adjacency matrix A each node is represented by a row as well as a column, a connecting edge independent of direction or weight is denoted as a 1 at the crossing position. If the strength of interaction needs to be analyzed this unit value is replaced by the preferably normalized weight of a directed interaction $w_{i,j}$ and leads to the weighted adjacency matrix A_w . Then the mentioned characteristic values defining the role of a player are easily obtained as:

$$\bar{1}^T \cdot A_w = \overline{PS} \quad \text{and} \quad \left(A_w \cdot \bar{1}\right)^T = \overline{AS} \tag{1}$$

These findings correspond very well to well-known structural parameters of social and other networks and allow extending them:

- For unweighted adjacency matrices the vector AS equals PS and yields the particular role (= degree) as components. Otherwise appropriate weighted in-degrees and out-degrees are defined accordingly and represent the local impact on members of the network or the influence a member has on its adjacent neighbors.
- The average active sum exactly mirrors the impact parameter ς of a network according to Zimmermann/Eber [42], within a closed network $\xi = \varsigma$ also reflecting the parameter of connectivity $\nu=(\xi+\varsigma)/2$:
$$\left[\left(A \cdot \bar{1}\right)^T \cdot \bar{1}\right] / N = \left\langle \overline{AS} \right\rangle = \varsigma = \nu \,. \tag{2}$$
- The same is valid for the average passive sum equal to the parameter of influence ξ:
$$\left[\left(\bar{1}^T \cdot A\right) \cdot \bar{1}\right] / N = \left\langle \overline{PS} \right\rangle = \xi = \nu \tag{3}$$
- The density of a directed graph thus becomes $D=K/n(n-1)$ [38]. Introducing normalized weights $w_{i,j}$ and $W=\sum w_{i,j}$ the weighted density is $D_w = W / n(n-1)$

Yet this linear understanding does not take into account the repetitiveness of interaction in a system during its development or more importantly, its convergent or divergent behavior. Therewith a number of (possibly weighted) paths through a network and from this closed path loops and feedbacks occur and gain importance. However, the approach can easily be extended to handle multiple interactions by making use of the power of adjacency matrices. I.e. the square of A provides the number of paths with length 2 from the source node to the sink node. More generally according to Katz [21], with $A_{i,j}^{k} = \left(AA^{k-1}\right)_{i,j} = \sum_r A_{i,r} A_{r,j}^{k-1}$ we obtain

- $A_{i,j}^{k}$ as the number of paths with length k from node i to node j, (4)
- $\sum_{k=1}^{m} A_{i,j}^{k}$ as the number of paths with length <=m from node i to node j and (5)
- $\sum_{k=1}^{m} A_{i,i}^{k}$ as the number of closed loops with length <=m where node i is involved. (6)

Making use of this we obtain higher order active and passive sums as well as a parameter indicating the degree of recursiveness of the graph. They can be treated equivalently to AS and PS determining the role which an aspect or participant plays within the system but include the behavior of the system up to the m^{th} step of time-development. Thus true long-term roles can be determined from higher powers of A:

- $\left[\vec{1}\right]^{T} \cdot \left[\sum_{k=1}^{m} A_{i,j}^{k}\right]\Big|_{r} = \overline{PS}\Big|_{r}^{(m)}$ the normalized passive sum, of degree m (7)
- $\left[\sum_{k=1}^{m} A_{i,j}^{k}\right] \cdot \left[\vec{1}\right]\Big|_{r} = \overline{AS}\Big|_{r}^{(m)}$ the normalized active sum of degree m (8)
- $\sum_{k=1}^{m} A_{i,i}^{k} = L_{i}^{(m)}$ the sum of weighted loops with length <=m where i participates (9)

Remark: Unnormalized parameters AS and PS tend to become very large as influence shares are cumulated. Nevertheless they reflect the correct value if the weighting is defined appropriately. Normalization would then have no effect on the activity Q of a variable as it is given by AS/PS while criticality P as $PS*AS$ remains a relative value.

An indicator of recursiveness –yet not equal but correlating to the definition of Zimmermann/Eber in [42] can be derived from the trace:

$$\left[Tr\ L_{i}^{(m)}\right] / N = \left[Tr \sum_{k=1}^{m} A_{i,i}^{k}\right] / N = \beta^{*} \tag{10}$$

3.3. Excursion: Consideration of complexity

Finally the classical parameter of complexity α can be obtained from the number of interactions $K=\xi N=\varsigma N=\nu N=\overline{PS}\cdot N=\overline{AS}\cdot N$ as:

$$\alpha = \frac{\ln(K/N+1)}{\ln N} = \frac{\ln(\nu+1)}{\ln N} = \ln_{N}(\nu+1)\cdot \tag{11}$$

Complexity is understood as the logarithm of the average influence of a node – including the unity-influence on itself - to the base of the number of available nodes. Amongst a vast multitude of definitions for complexity this one is based on the degree of information required for constructing the network in accordance with Shannon [32]. Therewith we obtain α as the average information of every node in connection to adjacent nodes expressed in terms of maximum available connections. Such understanding is compatible with the relative entropy of a node. The total average entropy H of a node turns out to be the same:

$$H=-\sum_i p_i \ln p_i = -\sum_{i=1}^{\nu+1} \frac{1}{\nu+1} \ln \frac{1}{\nu+1} = -(\nu+1)\left(\frac{1}{\nu+1} \ln \frac{1}{\nu+1}\right) = -\ln \frac{1}{\nu+1} = \ln(\nu+1) \tag{12}$$

3.4. Long-term behavior and stability

The operation of interactivity-networks is strongly time-dependent. Yet the emergent role of singular nodes respectively participants due to the locally defined properties of edges is only determined observing the state of equilibrium. As in fact networks are operated far away from such state the outcome may be questionable in detail but nevertheless long-term evaluations are expected to provide useful indicators characterizing stability. Therefore the mentioned degree m needs to be observed to infinity. To begin with every aspect/participant is given an arbitrary initial weight $\overline{W}^1 = \bar{1}$ (vector-of-ones). Then applying A on the weight a number of times yields the respective influence of adjacent nodes with their actual weight. Proceeding to infinity - if converging - the vector of weights will change no more, yielding the stable final relative weights of nodes $\overline{W}^\infty = A_{i,j}^\infty \cdot \bar{1}$. This is independent of the initial weight choice and of in-between normalizing the resulting matrix in order to keep the calculations within the numerically accessible range.

This procedure is identical to evaluating the Eigenvectors $\overline{V}$ of A. When stabilized, we obtain:

$$A \cdot \left(A^{k-1} \cdot \bar{1}\right) / \lambda_n = A^{k-1} \cdot \bar{1}, \text{ which is } A \cdot \overline{V_n} = \lambda_n \cdot \overline{V_n}, \tag{13}$$

Then $\overline{V_n}$ is the Eigenvector and the normalization λ_n is the corresponding (maximum and dominant) Eigenvalue

$$\overline{V_n} = \overline{W}^\infty = A_{i,j}^\infty \cdot \bar{1}. \tag{14}$$

At the first glance being being just a final distribution of weights after stabilizing the Eigenvector turns out to be a classical means to measure centrality of a node. Centrality of a node and respectively Centralization of a graph are fairly important parameters characterizing functionality of social networks. However temporal project networks can be measured and judged by the same. Well-known centrality parameters are e.g. ([3][22][12][13][14][15]):

- Degree-Centrality, where the number of In/Out-Edges measures the importance of a node [3].
- Closeness-Centrality is given by measuring the average distance of a node to each other (e.g. [2]).
- Betweenness-Centrality counts the number of geodesics between each pair of nodes the considered node sits on and therefore claims influence [13].

The Bonacich Power Centrality [4][5] states that the power of a node is determined by the average of the powers of the adjacent nodes which is identical to the Eigenvector algorithm described before. The complete Bonacich approach additionally includes a controllable soft transition to the degree-centrality which is of no further interest here. The Page-Rank Algorithm [27][28] used to evaluate the power of a webpage is based on a similar mechanism.

From the point of view of Theory of Systems Eigenvalues have a very specific meaning for the stability of systems [1][19] which is of interest when designing operatively working networks. In the long-term development each node is per time unit modified by a linear function of the actual state of all adjacent nodes. Then the system can be expressed as a set of linear differential equations (eventually shifted by an offset to the stationary states of 0):

$$\frac{\partial Q_i}{\partial t} = f(Q_j) \stackrel{!}{=} \sum a_{i,j} Q_j \quad \forall i \tag{15}$$

Any (weighted) adjacency matrix denotes the (linear) influences of a state given by a state-vector S on the future state by its modification during one progression step

$$\frac{\partial \overline{S}}{\partial t} = A \cdot \overline{S} \tag{16}$$

Such systems can be solved if A is diagonizable. Then the Eigenvalues λ_i form the values on the diagonal. Solutions would thus be of the type

$$\overline{S}_i \,\square\, \sum \exp\left(\lambda_j t\right) \tag{17}$$

Hence possible interpretations for the resulting set of Eigenvalues would be:

- All Eigenvalues being of real type implies no possible oscillations
- Real and negative: the system is stabilizing, where $-\lambda_j$ is the time-constant: $\exp(-\lambda_R t)$
- Real and zero: the system will be time-independent and stable: $\exp(0)$
- Real and positive Eigenvalues indicate exponential growth: $\exp(\lambda_R t)$
- Complex: imaginary part will solve to periodic fluctuations, damped or possibly escalating according to $\exp((\lambda_R + i\lambda_I)t) = \exp(\lambda_R t)(\cos\lambda_I t - i\sin\lambda_I t)$ where the frequency of oscillation becomes $\lambda_I = \omega_i = 2\pi f_i$.
- Complex with a negative real part: the system is likely to loop and approach a fixed point
- Complex with a positive real part: the system will oscillate around a fix point

In the case of analyzing Cross-Impact-Matrices for networks mapping the interactivity of participants in a social or temporary organizational system we derive therefore: As long as the adjacency matrix is used all values are 0 or 1 and A is symmetrical. Investigating real Cross-Impact- Adjacency Matrices are weighted by positive strength values e.g. $[0..1]$. Then all Eigenvalues are of real type and the respective systems are rarely stable ($\lambda_n < 0$) but developing. Thus we will have in any case exponential growth, probably decrease as well. Therefore the only point of interest is which item would dominate the growth where all others are reduced by continuous normalization ([29][16][31]). According to the Frobenius-Perron Theorem a dominating positive Eigenvalue and an associated positive Eigenvector can be derived which determines the long-term behavior of the system and therewith may serves as a characteristic property of the network.

3.5. Laplace Matrix

The transition from dominant Eigenvalues to strictly dominant Eigenvalues rests on the condition of $A^k > 0, \textit{ for a } k \in \square^+$, which is equivalent to the existence of at least one singular path between any two nodes. This condition corresponds to the property of irreducibility of the graph, i.e. the graph does not decompose into components. Therefore means to measure the degree of decomposition, i.e. connectivity are required and given by the Laplace-matrix $L=D-A$ (Diagonal matrix of node degrees D minus adjacency matrix A) in accordance to e.g. Chung [7][8] or Spielman [35]. We always obtain $\lambda_0 = 0$ as the smallest Eigenvalues of L since rows sum up to zero and therefore $\bar{1}$ is the Eigenvector $L \cdot \bar{1} = 0$. Furthermore the multiplicity of this Eigenvalue $\lambda_0 = 0$ reveals the number of components a graph decomposes into ([6][9][10][11][23][36]). This can be calculated easily by solving the characteristic equation for L for roots at $\lambda_0 = 0$ and eliminating consecutively roots $\lambda_0 = 0$ until no more are obtained at position zero. Therewith the number of elimination steps c yields the number of connectivity components of the network. Since this works well on weighted graphs the degree of decomposition of a network can be directly observed and used as a further key indicator for the development of independent subgraphs.

4. Conclusion

The most essential virtue of an organizational structure in particular for non-recurring projects where no test runs are available are its predictable stability and its functionality in terms of desired states. It would be formed by predefined participants and their respective dependencies partly given by the situation (e.g. technical or legal dependencies) partly designed by the project managing authorities via contracts and rules (e.g. responsibility, decision making, being reported to etc.). This would e.g. apply to

- Communication within social networks as well as in participants interaction in construction projects
- Trading in economy, interaction of players on markets, analysis of locations and quarters
- Flow of Decisions and Reports, failure progression, distribution of risk and uncertainties in projects
- Cooperation within consortiae, stakeholder analysis, analysis of influence in rental contracts

We propose the use of the parameters $\overline{PS}^{(\infty)}, \overline{AS}^{(\infty)}, \overline{L}^{(\infty)}$ to characterize the specific impact-roles of the participants within the organization. Such would allow assessing, appraising or constructing organization networks on the basis of known well-established structures.

Furthermore the careful analysis of the Eigenvalue spectrum λ_n of the network or preferably the design of organizational networks according to such aspects is recommendable in order to judge the temporal stability and the tendency to approach unwanted or desired equilibrium scenarios and states. Node-weights and appropriate states would possibly be formed e.g. by

- Rates of financial flows, where the equilibrium is the final distribution of capital
- Weighted degree of decision making, where the equilibrium will be the degree of responsibility
- Material flows would be modelled and the equilibrium will be the need for storage over given time frames
- Flows of abstract or real production factors. Then equilibrium weights reflect the the particular creation of value

Therefore we demand a properly designed structure of interaction within a project to be at least stable on the long-time scale. I.e. a strongly dominant Eigenvalue λ_0 would be required where the associated Eigenvector $\overline{V}_0$ mirrors a fairly well preferred state which would be the function of the organization as it was designed for. Then λ_0 reflects the stabilizing time constant to reach this intended functionality which we want to be as large as possible since the characteristic time of convergence is $\tau = 1/\lambda_n$.

The total spectrum λ_n beyond that will reveal the further character of the analyzed organizational network. All Eigenvalues λ_n and the associated Eigenvectors $\overline{V}_n$ reflect the networks future behavior. The possible states (=Eigenvectors) should be preferred ones (i.e. at least acceptable scenarios) and be reached within sufficiently short time $\tau_n = 1/\lambda_n$ as we would like to design cooperative networks short-time stable.

This can be easily accomplished e.g. by the proposed constructional approach according to Zimmermann/Eber [40] where additional nodes (control processes) were introduced. At the first glance these processes increase options of complexity since they would strongly interact with the existing nodes (production processes). Yet they would force the outcome of the production processes into very small corridors which are precondition to subsequent production processes. Therewith the interconnectivity of the production nodes is strongly reduced by the operation of the added control nodes. The main consequence would therefore be the falling apart of the most complex network into a set of small world scenarios which are subject to only very few clearly assessable sets of Eigenvectors and Eigenvalues determining their behavior. Thus the construction of appropriate networks with clearly predictable sort- and long-term stability and outcome is possible and can be proven easily.

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