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Managing Construction Projects: Developing Complexity into Complicatedness

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Abstract. Construction projects are understood as being complex and therefore in need of support through adequate tools to be successfully managed. Among others, the Building Information Model (BIM) is expected to provide a modern and powerful toolset allowing for reliable prediction of the respective development and behaviour. Based on Theory of Systems, the term of complexity in fact matches the principal capabilities of an object-oriented information system where e.g. the Building Information Modelling rests upon. However, any complex system tends to instable behaviour allowing principally for no reliable prediction, in particular in the single run required for unique projects with no possibility to rearrange processes without major losses. Correspondingly, experienced Construction Managers are judging the complexity of projects as a crucial obstacle to efficient execution but declare complexity as not measureable, thus as degree of unmanageability. Therefore, the inherent complexity of interdisciplinary projects needs to be reduced, i.e. transformed into complicatedness, not reducing the effort of elaboration but allowing for stable solutions. In order to achieve such a transfer, the inherent heterogeneity is utilized tracking down the strictness and linearity of the internal and external system borders, thus, investigating the separability of the adjacency matrices. These mainly topological considerations lead to criteria forming substructures finally allowing for predictable behaviour of the project structures with limited uncertainty. Therefrom, we expect some significantly improved understanding of the cybernetics of projects and consequently advanced possibilities in shaping and establishing activity-based risk management, which is crucial to nowadays construction and real estate projects.

1. Introduction

The introduction of Building Information Models (BIM) is currently expected to solve a wide range of construction problems [1]. Resting upon the principles of object-oriented database theories [2], this approach is bound to modelling the complete entirety of elements required for construction and their respective interactions [3]. If in particular the completeness of this model can be ensured undeniably the behaviour of the system can be predicted in detail [4] [5]. Thus, the expectations are based on the human ability to describe a very encompassing unstructured entirety with utmost precision [6]. Besides the fact that many issues required for operational prediction, like contracts, dates and operational i.e. capacity-induced interactions, are principally not available in advance [7], the major problem results from the system's inherent complexity, leading to unstable and therefore nevertheless unpredictable solutions [8][7]. Since the object-oriented approach of BIM is intentionally in no way restricted to systems of low complexity, the principal accessibility of prediction limited due to more

abstracts reasons needs to be investigated. Thus, this article focusses on the term of complexity [9] and the therewith resulting inherent issues.

2. Definitions of Complexity
Considering the term of complexity [10] of a system, in particular complexity of the organisation of a project, some confusion exists.

2.1. The Understanding of Complexity in Construction Management
Recent surveys among project managers [11] reveal that complexity is considered to be an existing characteristic of a project, but state it not to be accessible by any kind of measurement. If this would be true, the parameter complexity would serve only as the description of the degree of a project to be not predictable and therefore not manageable. Then, any so-called "complex" project may under no circumstances be initiated since the expected result can in no way be achieved with some certainty. So, either projects are tackled on the background of hope and accidentally succeed or means of dealing with a high degree of complexity are available and hidden beyond the surface of management [12].

2.2. Theoretical Definitions of Complexity
Even if this understanding is more semantical at least the central idea is given by distinguishing between complex and just complicated behaviour. Caldarelli and Vespignani [13] state the criteria for complexity first as heterogeneity over all scales, indicating that average values are not representing the system's characteristics and second as being irreducible, i.e. any attempt of separating parts of the system leads to a fundamentally different behaviour [14]. These criterions in fact allow for no statistical description and therefore represent the absolute limit of unmanageable structures due to complexity. However, in order to transform organisational structures into manageable units, substructures need to be identified which can be treated separately without changing the system's behaviour significantly [15]. Thus, truly complex systems remain complex, but if they were separable to some degree the task would be to eliminate exactly this amount of complexity. Then, based on statistical methods incomplete complexity may be transformed into complicatedness, i.e. into a set of widely independent subsystems with less complexity. On this background, based on Systems Theory, several mathematical definitions of complexity are possible, which are mainly compatible to each other, leaving the difficulty with the translation of organisational systems into abstract systems. The parameter of complexity may be defined as

$$\alpha = \ln(\xi + 1) / \ln N \tag{1}$$

where N represents the cardinality, i.e. the number of primitive elements within the system, and K counts the interactions between them. The interoperability $\xi = K / N$ equals the average number of (directed) interactions per node [16]. In the following, this formal definition is subjected to more meaningful interpretation:

2.2.1. Measure for the Interaction Degree of Primitives. As a classical approach, the parameter connectivity focusses on the number of interactions K within the system related to the number of primitive elements. Based on the known cardinality N and K the complexity is just a logarithmic measure, scaled in a way that maximum connectivity, i.e. each element is connected to each other element, leads to $\alpha = 1$ [17].

2.2.2. Measure for the Relative Information of a Node. The local information of a particular node, based only on structures, is proportional to the number ξ of nodes actively connected to, i.e. where a local token may be transferred to. ξ needs to be increased by 1 to cover the node itself as a possible additional target of the information. According to [18], the information is measured as logarithm of the options, in this case related to the maximum available number of target options which is N. Then,

complexity represents the average entropy of a node in comparison to the possible entropy according to Shannon [18]: $E_R = \ln(v+1)/\ln N = \alpha$ [18].

2.2.3. Degree of Emergence of a System's Behaviour in Contrast to Complicated Behaviour. Describing complexity by the number of states a system can occupy leads to a similar explanation. At a certain point of time, the considered system is defined by a multidimensional state within the space of states. Focusing mainly on the dynamics of a system, complexity can be defined by the number of states which are available for a next step which is given by the transition from one state to any logically following step. This is only possible along the directed interactions which are represented again by the interoperability $\xi = K/N$ out of N states available. Then, the logarithmic measure for the number of available states is the given complexity α [17].

2.2.4. Dimension of the Configuration Space of a Project Structure. Positioning all elements in a way that each is the spatial next neighbour to all the targeting elements requires a virtual space with a number of α dimensions. Thus, complexity represents the dimension of the configuration space scaled to a maximum dimensionality of 1, where all nodes can be placed respectively [18].

2.2.5. Degree of Non-linearity of Propagation Deviations. Furthermore, α is determined as the exponent of the structural development of a modification $\Delta(\zeta)$ from one causal situation r to a next logically depending situation r+1. Thus, α reflects the degree of the linearity of the structural development $T(r) \simeq \xi^{1+\alpha r}\Delta(\zeta)/(1-\beta)$ with increasing structural steps r and the positive factor with each step $\omega \simeq \xi^{\alpha}$ [20].

2.3. Complex Solutions to Systems Theory Differential Equations.
Systems Theory describes the behaviour analysing the linear Taylor terms of functions which represent the interaction of nodes. For a set of linear differential equations the solutions are of the type

$$n_i : \frac{\partial Q_i}{\partial t} \simeq \sum_j c_{i,j} Q_j \qquad Q_i = \sum_j g_{i,j} e^{\lambda_j t}\left(+\sum_j g'_{i,j} e^{2\lambda_j t} + ...\right)$$

Without limitation to the generality, the solutions [21] are either oscillating, exponentially escalating or in rare cases approaching constant values. Therefrom, the authors conclude the restriction to very clear structures in order to maintain predictable systems' behaviour which is the same as manageable systems. Finally, graph-theoretical tree-structures and network-structures are the only remaining options which correspond well to the common understanding. In this paper, a different, however supporting approach is taken leading to a similar result but based on an investigation of a critical transition in consuming resources.
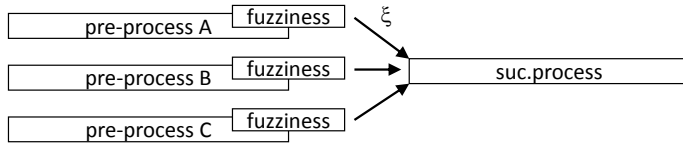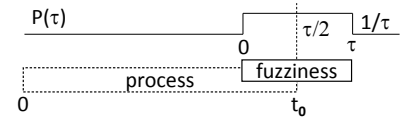
3. Critical Point of Complexity
A fairly simple consequence of complexity would be the asymmetrical distortion of average values due to higher interoperability values $\xi > 1$ if intermediate results are subject to limited uncertainty [22]. A purely sequential system corresponds to $\xi_{lin} = 1$ and therewith $\alpha_{lin} = \ln 2/\ln N$. In this situation, the central limit theorem states average values of e.g. duration or consumption of resources for the whole system equal to the singular elements. However, increasing $\xi > 1$ leads to a loss of efficiency due to the absolute requirement of the contemporary readiness of all prerequisites for the subsequent process. In the following, this is presented exemplarily for the duration of processes but holds true for resources and products as well.

3.1. Local Consideration
Let the duration t of a process vary around a fixed value based on a constant distribution (figure 1 and figure 2): $t = t_0 \pm \tau/2$ respectively $t = t_0 - \tau/2 + \tau'$, where τ' is a random variable, according to the distribution

$$P(\tau') = \begin{cases} \tau^{-1} & if\ 0 \leq \tau' \leq \tau \\ 0 & otherwise \end{cases}.$$ (2)

Figure 1. Definition of interoperability   **Figure 2.** Probabilities of fuzziness

This distribution is normalised and, thus as expected, the average value is

$$\overline{\tau_1} = \int_0^\tau \tau'\tau^{-1}d\tau' = \frac{1}{2}\frac{\tau'^2}{\tau}\bigg|_0^\tau = \frac{1}{2}\frac{\tau^2}{\tau} = \frac{\tau}{2}$$ (3)

Combining two predecessors PrA and PrB into one process leads to the probability P of PrA times the probability, that process PrB is already finished, and *vice versa*. Any process duration "finished before" is determined:

$$P_{before\ \tau'}(\tau') = \int_0^{\tau'} P(\tau'')d\tau'' = \frac{\tau''}{\tau}\bigg|_0^{\tau'} = \frac{\tau'}{\tau} \qquad P_{Pr A \& Pr B}(\tau') = 2P(\tau')\cdot\frac{\tau'}{\tau} = 2\cdot\frac{\tau'}{\tau^2}$$ (4) (5)

Thus, we find as average time for the combined situation:

$$\overline{\tau_2} = \int_0^\tau \tau' 2\frac{\tau'}{\tau^2}d\tau' = \frac{2}{3}\tau$$ (6)

For each number of preceding processes to be taken in, the overall probability is a factor $1/\tau$ for the primary process, the number of processes to have finished before as they can be replaced by the primary process and a factor τ'/τ for each process that needs to have finished before. Thus, the probability for a number of ξ processes to be taken in is:

$$P_\xi = \xi\frac{1}{\tau}\left(\frac{\tau'}{\tau}\right)^{\xi-1} = \xi\frac{\tau'^{\xi-1}}{\tau^\xi}$$ (7)

The therefrom derived average time is

$$\overline{\tau_\xi} = \int_0^\tau \tau'\xi\frac{\tau'^{\xi-1}}{\tau^\xi}d\tau' = \frac{\xi}{\xi+1}\tau$$ (8)

Remark: The worst case scenario is considered $\overline{\tau_\xi} = \tau/2$ where the indeterminacy is completely turned into reality and therefore to be avoided by any means. Approaching this situation is described by average relative losses $\tau = 2\tau/\tau$ respectively as add-on to the $\xi = 1$ situation

$$\tau_{add} = \frac{2\xi}{\xi+1} - 1 = \frac{\xi-1}{\xi+1}$$ (9)

As can be expected, this equals zero for $\xi = 1$ (linear sequence, no add-on to the average duration of a single process) and approaches unity as the worst case of the given distribution for $\xi \gg 1$. This result can be easily formulated dependent on complexity α and volume, i.e. cardinality N of the system. With $\alpha = \ln(\xi+1)/\ln N \rightarrow N^\alpha - 1 = \xi$ we obtain:

$$\tau_{add} = \frac{N^{\alpha} - 2}{N^{\alpha}} = 1 - 2N^{-\alpha} \tag{10}$$

This yields a value very close to the worst case for maximum complexity $\alpha = 1$ if only the number of elements is large enough. The minimal complexity for a linear chain is

$$\tau_{add,\min} = 1 - 2N^{-\alpha_{\min}} = 0 \tag{11}$$

3.2. System-wide Consideration

Within a system, repeated recombination of fuzzy processes needs to be taken into account. Causal interdependencies lead to a system structure, where all elements are ordered according to ranks. Thus, the maximum number of ranks Γ according to the Theory of Graphs describes the maximum length of any causal chain within the considered system. The density $\rho = N / \Gamma$ denotes the average number of elements on the same rank. On each rank r the number of ξ elements are combined and operate on a single element at r+1. Combining ξ elements on a singular rank position differs in no way from combining some elements on r+2 where these are combined from ξ elements on r+1. Therefore, only the number of elements combined on all rank positions needs to be known in order to elaborate the statistical add-on to the overall result. Since on each rank, each element combines from ξ elements, the result comprises the combination of ξ^{Γ} elements. Therewith we obtain for the total system:

$$T_{add} = \frac{\xi^{\Gamma} - 1}{\xi^{\Gamma} + 1} = \frac{\left(N^{\alpha} - 1\right)^{\Gamma} - 1}{\left(N^{\alpha} - 1\right)^{\Gamma} + 1} \tag{12}$$

The following graph (figure 3) shows the dependency on the cardinality N, the complexity α and the maximum rank Γ.
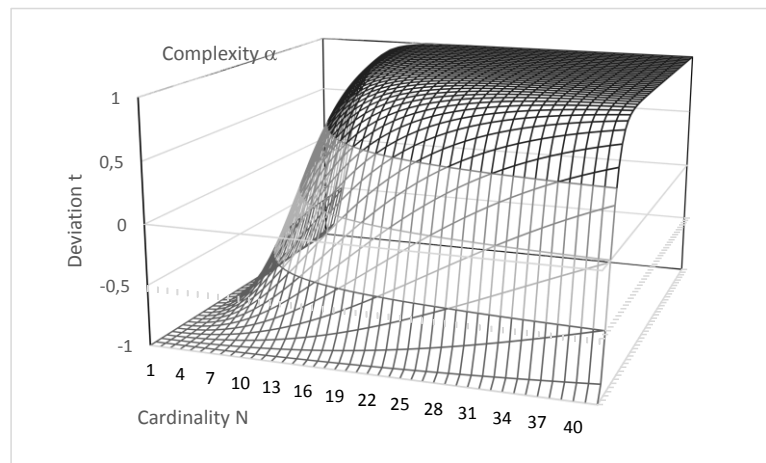

Figure 3. Critical transition of add-on T_{add} *vs* N and α .

The add-on is quickly rising to the worst case for higher cardinality or/and higher complexity. With increasing Γ, the transition becomes very steep and therefore marks a limit of criticality, which is described by

$$0 = T_{add} = \frac{\left(N_c^{\alpha_c} - 1\right)^{\Gamma} - 1}{\left(N_c^{\alpha_c} - 1\right)^{\Gamma} + 1} \quad \rightarrow \quad 0 = \left(N_c^{\alpha_c} - 1\right)^{\Gamma} - 1 \tag{13}$$

$$\alpha_c = \frac{\ln 2}{\ln N_c} = \alpha_{lin} \tag{14}$$

The critical transition lies exactly where complexity equals the value given for a linear chain. Thus, for any substantial Γ we obtain strongly increasing losses due to complexity as soon as the limit of linear chains is exceeded. Still smaller values α indicate the breaking up of the system into smaller subsystems, where at least some elements have no successor and therefore no part in influencing the rest of the system anymore. The derivative with respect to ξ reveals the behaviour at this border:

$$\left.\frac{\partial}{\partial \xi} \mathrm{T}_{add}\right|_{\xi=1} = \left.\frac{2\Gamma \xi^{\Gamma-1}}{\left(\xi^{\Gamma}+1\right)^2}\right|_{\xi=1} = \frac{\Gamma}{2} \tag{15}$$

The rise of loss is closely coupled to the length of causal sequences Γ. Close to unity, i.e. for negligibly short logical chains, they play no role. Yet as they become longer as is typical for projects, they reach substantial values. Considering the scales of $T_{add}=1$ as the worst case, this is particularly large as soon as Γ reaches values of significantly more than 2.
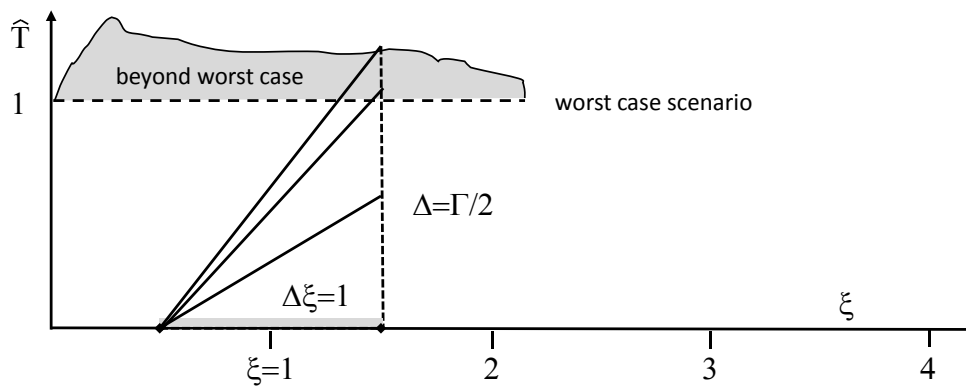

Figure 4. Scaling of derivative at the critical transition

Furthermore, the development close to criticality with respect to N and α can easily be achieved by differentiation. With $N^{\alpha}-1=1 \rightarrow N=2^{1/\alpha}$, we obtain

$$\frac{\partial}{\partial \alpha} \mathrm{T}_{add} = \left.\frac{\partial}{\partial \xi} \mathrm{T}_{add} \frac{\partial \xi}{\partial \alpha}\right|_{\xi=1} = \Gamma \ln N \tag{16}$$

and

$$\frac{\partial}{\partial N} \mathrm{T}_{add} = \left.\frac{\partial}{\partial \xi} \mathrm{T}_{add} \frac{\partial \xi}{\partial N}\right|_{\xi=1} = \frac{\alpha \Gamma}{2^{1/\alpha}} \tag{17}$$

Thus, at the brink of complexity, losses are rising further proportionally to $\ln N$ which does not compensate for the proportionality to Γ or viewed in regard of complexity α with a factor $\alpha / 2^{1/\alpha}$. Here, only low complexity $\alpha \ll 1$ in comparison to low Γ, i.e. short causal chains, are of help. According to figure) e.g. complexity of $\alpha \approx 0,45$ at max would just compensate for causal chain lengths of unrealistically low $\Gamma \approx 10$ for a worst case, but only $\alpha < 0,15$ is capable to secure such a situation to at least a few percent of complete indetermination.
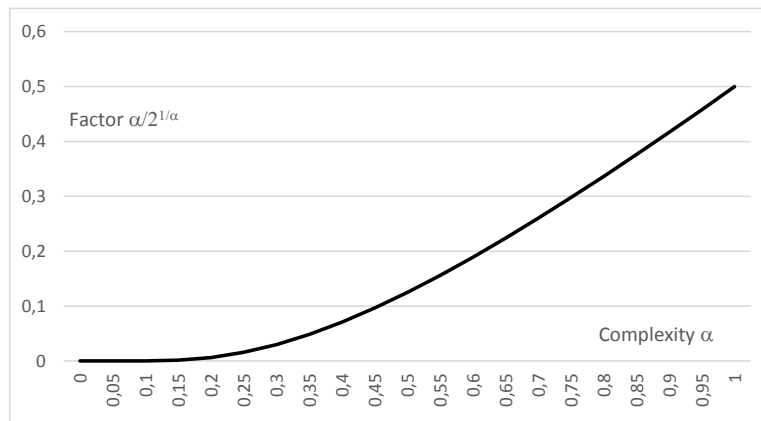
Figure 5. Factor eventually compensating for Length of Chains Γ

In both cases, as long as not all variables are perfectly well-known and not varying, i.e. $\tau = 0$, close coupling of processes leads to unbearable losses and must be avoided by all means. On this background, we conclude the general unmanageability of complex systems.

4. Reducing Complexity

Complexity is defined through the characteristic of a system that no element nor an interaction can be removed or ignored without modifying the systems' behaviour significantly [14][23]. On this background, in fact, no improvement on tackling the situation can be offered [24]. Yet, the question is whether real systems are factually that complex or can be separated into smaller subsystems, which act individually and are mainly not interfering with the remaining system. Then, the overall-behaviour would be just a linear concatenation of the subsystems, which is just complicated, since it demands only industriousness and effort to understand and describe the behaviour, but is principally possible – in contrast to truly complex systems. This leads to an investigation of the separability of a system, formally identical to the question of to which degree the adjacency matrix representing the systems interactions is separable into independent submatrices [25]. Considering the adjacency matrix includes the localisation and sorting out the singular elements, i.e. elaborates the systems' behaviour on local levels [26]. In order to judge a system on a more general level, adequate homogeneity is presupposed since only then statistical reasons will hold [13]. The demand of reducing complexity in order to increase manageability is here given by the attempt to minimize complexity losses. As already mentioned, a different approach by modelling the system via a set of linear differential equations and considering characteristics of stability [27] leads to the same conclusions.

4.1. Issues from Minimizing Losses

The strong dependency of losses on ranks Γ emphasizes the importance of rank-sorted structures, i.e. causal sequences, where cause and effect are clearly defined. This in particular enforces to avoid any fuzzy structures which can not be formulated as graphs.

4.1.1. Loop-Freeness. Obviously, high values of Γ indicate a very high positive gradient close to the $\xi = 1$ limit. This leads to the conclusion that in any case long causal chains need to be broken up. In particular, loops need to be eliminated completely since they principally lead to infinite values of Γ .

4.1.2. Control-Loops. If loops are very short, i.e. eventually comprising only two corresponding elements, the consideration is on a different basis. Such very local loops with no further impact may be understood in detail, therefore used in particular to stabilize elements as negatively effectuating control loops, exhibiting partly oscillating behaviour but dampened with reasonably short time constants. In this case, the behaviour is well understood and is not subject to the overall consideration of stochastic impact. However, since they would stabilize variables, they are strongly contributing to

the separation of systems, as they lead to a high degree of independency of formerly strongly coupled segments [28].

4.1.3. Multiple Paths. The exceedingly high gradient of losses is bound to the multiplicity of impact. This implies the need to prefer structures, where impact is being distributed over the graph, but never united. On the background of these arguments only two well-known graph-theoretical structures [29] [30] [31] remain as the goal of restructuring complex systems.

4.2. Resulting Structures Tree and Network
Unidirectional tree-structures maintain clear ranking, no multiple paths and absolute freedom of loops. Since they certainly cannot model complete (complex) systems, they need to be used in particular to operate definition and responsibility issues. Including very local control-loops, for clear structural reasons, absolutely safe results can be constructed and finally obtained. All further interaction must be subjected to graph-theoretical networks [32]. Allowing for almost all kind and number of interactions, which cannot be avoided in production, at least ranks and freedom of loops is enforced. The remaining problem due to multiple paths and possibly high impact-values ξ, however can easily be tackled by subjecting the singular elements, i.e. subsystems, to local control-loops which would ensure the correct (according to the given unambiguous definition) outcome of the elements.

5. Conclusion
Summarising, we obtain a very plain methodology to treat complexity in organisational structures. In any case, complexity itself can not be cured but only reduced, i.e. by eliminating the tightness of interactions. Therewith, the former large complex system becomes separated into a set of less complex subsystems which can be understood and handled more easily. The resulting modified system comprising the subsystems is only helpful if this is less complex than the original, i.e. interactions are less and simple, ideally just a linear combination of the subsystems. Compatible with common understanding, but based on a much more substantial consideration, the resulting structures need to be either graph-theoretical tree-structures or rank-sorted, loop-less graph-theoretical networks. Possibly multiple but strict tree-structures serve to ensure completeness and systematical correctness of the elements to be identified. Separated from this elaboration structure, these elements may be (re-) subjected to their interaction on the basis of well-ordered networks. Factually complex systems would not allow for such ordering due to being irreducible by definition. However, in many cases, hidden separability to some degree is given and the attempt of applying these strict structures reveals less than assumed complexity. Otherwise, in order to artificially produce independency, short control-loops need to be applied. Based on dampening loops, random result variations of processes are forced back to tolerance corridors around the designed values so that successor processes are no more dependent on the exact performance of the predecessors. Within tree-structures, they help separate branches (horizontally) as well as keep hierarchical levels (vertically) apart. In network structures, they serve breaking up causal loops and shortening causal chains in longitudinal direction. Then complexity is transferred into mere complicatedness, where emergent behaviour is replaced by a larger set of independently operating subsystems and their local behaviour. To tackle this, only industriousness is required, but predictable solutions are principally available.

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