CPM Stability in Complex Projects and Systems.

Niv Yonat[1]
Igal M. Shohet [2]

ABSTRACT

Critical Path Methods fail in complex projects. This article portrays how they fail, why they fail, and what remedies may be suggested, if at all. Capitalizing on morphological similarities, the research of complex projects' CPM is coupled by research of complex infrastructure. Falsification procedure is applied to some common mathematical tools for stability analysis taken from evolutionary graph theory and network theory. Demonstration of morphology and risk impact on networks stability, evolution, viability kernel, modeling limitations, and on Entropy, is performed. Entropy has a pivotal role in explaining why various indexes such as criticality index and replicator equation lose their predictive capacity. The research analysis is conducted by numerical experiments, validated by case-studies, and evaluated by expertise. The contribution of this research is the addressing of the gap in understanding CPM systems failure, the suggestion of a possible predictive tool and the drive to return to the management of projects rather than the management of models. CPM is reduced to a descriptive tool for project management with a promising application to infrastructure management.

Key Words

CPM, Complex projects and infrastructure, Network stability, Project Management, Risk

INTRODUCTION

Critical Path Methods [CPM], such as PERT, are prevalent in construction. In many contracts CPM are mandatory. There are standard software with decades of experience, accumulated through multitude of versatile applications, feed-back and improvement. The systems integrate WBS, time, cost, cashflow, manpower, constraints and more, to produce block diagrams, Gant charts, excel worksheets, cashflow diagrams, resource allocation, and more. All these apparent coherent, productive, meticulous system culminate in failure to represent actual complex projects (Lerche et al., 2020).

The literature suggests that: "PERT/CPM systems are not suitable for Construction Management" (Ragel, 2021). There is a gap in the understanding why. Some suggest that the cause of failures is in modelling: "coupled activities often go undocumented and unnoticed in such diagrams" (Eppinger & Browning, 2012), or "Although the choice of elements to include in a system has always been a focus of system designers, relatively recent advances in complexity science have emphasized the critical role played by the lateral links among elements, particularly when it comes to the emergence of system behaviors". (Pinto & Slevin, 1987) suggested the ontological dependence on information

[1] Department of Civil and Environmental Engineering, Faculty of Engineering Sciences, Ben-Gurion University Israel. Corresponding author, mail: yonatn@post.bgu.ac.il

[2] Professor, department of Civil and Environmental Engineering, Faculty of Engineering Sciences, Ben-Gurion University Israel. Department of Civil and Construction Engineering, College of Engineering, Chao Yang University of Technology, Taichung, Taiwan, Republic of China.

and (Yonat & Shohet, 2022) the role of info-systems [together denominated here: "**Morphology**"] (Newman et al., 2002) studied avalanche generated by power law distributions of faults [fires] thus adding the statistics of faults as stability parameter. To these (Reason, 1990) add imported risk and latent faults [together denominated here: "**statistics**" or "**Risk**"]. All these suggestions are produced in this article [Fig. 24, Fig. 13, Fig. 23, Fig. 11 decision rules, Fig. 10, Fig. 19, respectively].
CPM fails in addressing information, feedback, and rework loops.
The objectives of this research are to examine CPM stability, to sort out stability criteria and explicatory factors, to propose whether Critical Path [**CP**] failure can be predicted, whether a CPM graph can be stabilized, and eventually to suggest complex projects and infrastructure time management paradigm.
The pursuit of the objectives yields a falsification of the applicability of CPM to complex systems and by and by of stalwart stability criteria.

DEFINITIONS and CONCEPTS related to CPM NETWORKS

Nodes in CPM are activities.
Edges in CPM are directed links between activities, setting precedence and WBS order.
Rank - the number of edges emanating from a node.
Outdegree - the number of outgoing edges was used here to represent rank for directed graphs.
WBS - **W**ork **B**reakdown **S**tructure.
DSM **-** **D**esign **S**tructure **M**atrix where [here] horizontal entries are "from", vertical are "to".
Adjacency matrix is a weighted DSM.
Laplacian is generated by the subtraction of the symmetric [non-directed] DSM from a unit matrix of the same dimension multiplied by the networks' nodes rank vector.
Eigenvalue/Eigenvectors are generated of the Laplacian matrices.
Criticality index [**CI**] is the probability of a CP
Viability Kernel

$$x(t) \in K \qquad (1$$

$$\dot{x}(t) \in F(x(t) \qquad (2$$

Here x is the state variable vector, $F(x_i)$ is the CPM recursive optimization procedure with stochastic time.
Replicator equation
Under the premises of CPM, Equation (2) is developed to Equation (4).
In evolutionary Graph Theory (Barahona & Pecora, 2002)

$$\dot{x} = F(x_i) - \sigma \sum_{j=1}^{n} \mathcal{L}_{ij} H_j \qquad (3$$

Where x_i is the state variable of H, L is the Laplacian and H the weighted adj. Matrix.
The threshold is:

$$F(x_i) \leq \sigma \sum_{j=1}^{n} \mathcal{L}_{ij} H_j \qquad (4$$

For our falsification endeavor there is no need to calculate the Lyapunov exponent, the use of spectral proportion suffices:

$$\frac{\vartheta_{max}}{\vartheta_1} \text{, where } \vartheta \text{ are eigenvalues of the Laplacian} \qquad (5$$

And for a directed Graph

$$\sigma_\mu^2 = \frac{1}{\partial^2 (N-1)} \sum_{i=2}^{N} |\mu_i - \bar{\mu}|^2 \text{, where } \mu_i \text{ are the Laplacian eigenvectors values} \qquad (6$$

Entropy $Etropy = -\sum_r p_r \, ln(p_r)$ (7
Where p is a state probability, $r=CP_i$
Ntropy is a parameter suggested in this work.
Ntropy is a normalization of Entropy to enable comparison between different systems:

$$Ntropy = -k_N \sum_r p_r \, ln(p_r)\,, \ k_N = \frac{1}{\frac{1}{n} ln \frac{1}{n}} \qquad (8$$

Attractors are paths [CP] that the system tends to prefer. Attractors act as minimum/maximum energy states that a net prefers under the excitation of a fault wave.
Risk here refers to faults PDF.
Imported Risk is risk that is "imported" through subcontractors and supply chains, through the infrastructure of the company [multi-project management cause cross effects] and via information networks. Design feeds faults to all, it feeds the info-system, creates faulty design and infrastructure, and causes rework. Design embeds faults and latent faults in all processes and products.
Synchronization in a CPM network is a system, say of two activities, connected start to start and finish to finish. In network analysis a loop is considered synchronized, in DSM a loop may be substituted for one hammock activity. In production line, synchronized are activities with the same frequency.
Reification fallacy: when models erroneously substitute for reality.
Minimum networks: Here, the minimum net that holds the min-required teleonomic information, replacing loops, feedbacks, and recurrent modular formations with hammocks.

METHOD

Falsification is carried out by numerical experiments and case-studies.

- ❑ Numerical experiments data and parameters
  - Five timetables
  - Two decision rules for faults correction.
  - Two PDF.
  - Iterations: 6,30,200,500 times.
- ❑ Case-studies
  - Pumping station-Jebeke C-2012-13 (Batselier & Vanhoucke, 2015)
  - Wind-farm C-2011-13 (Batselier & Vanhoucke, 2015)
  - Building a House C2011-10 (Batselier & Vanhoucke, 2015)
  - Pre-cast project (Shen et al., 2022)
  - Storm-water system (article in writing)
- ❑ Possible explicatory parameters subjected to falsification
  - Number of edges
  - Degree Rank
  - Laplacian power function power parameter "b"
  - Number of paths, number of alternative CP, attractors
  - Entropy and Ntropy
  - Laplacian STDV
  - Criticality Index [CI]
  - Replicator equation
  - Eigen ratio
  - Eigenvalue stdv
  - synchronization
  - Vibration modes: Eigenvector, eigenvalue refractions

The layout of this article is:
Following the **Definition**s and **Method** section, the research **Hypothesis** is proposed, next the **Results** section presents the experiments and their results, Case-studies analysis, and results, relating

to concepts and tools, and some insight generated by expertise (Heron & Reason, 1997). This presentation is followed by **Falsification** of the potential explicatory parameters and methods section.
The **Discussion** section follows with further insights and inferences relating to viability kernel and butterfly effects, off-site production effects on risk, synchronization, reification, information systems, attractors, further on the validity of the hypothesis is discussed, means to manage complex systems are suggested and a possible role for CPM.
The **Conclusion** summarizes the results, the discussion, and the contribution of this article.
The numerical experiments' data, morphology, statistics, explicatory parameters, and results are documented in **Appendix A**,
The Case-studies' DSM, Laplacian and traits, analysis tools application and results are given in **Appendix B**.

RESEARCH HYPOTHESIS

The stability of networks is determined by **statistics** and **morphology**.

(9) ToF *(Yonat & Shohet, 2022)* suggests that the relevant statistics is open faults' statistics, and the relevant morphology is the info-system's morphology.

Faults are defined as any error that penetrates the systems' barriers and, therefore, may generate a response [change order such as rework or repair] in the info-system. Fault may be generated by bad workmanship, materials deficiency, design mistakes, owner change orders, procurement channels errors and latencies, and so on. When an order is given, faults are corrected, otherwise faults propagate magnify and multiply to avalanche.

Barriers such as standards for materials, praxis for workmanship, specs for suppliers, peer review for design, and so on, prevent errors from entering the system. Once barriers are penetrated, the info-system has its chance to stem the faults at inception. Open [unresolved] faults are the pathogens of the system (Reason, 2000), causing disruption such as time overflow.

Open faults and only open faults generate duration overflow(9). Morphology multiplies, inflates, and propagates the faults.
Faults PDF is log-normal (Horvath, 1959).
Faults magnitude has a power function (Yonat & Shohet, 2022).
Power function is generated by the log-normal PDF (Yonat & Shohet, 2022), it is scale free; therefore, the same function provides for time, cost, and magnitude of faults with only a change of a scaler.

EXPERIMENTS, CASE-STUDIES, and RESULTS

Experiments

CPM1 [Appendix A] is an adjacency matrix of 24 activities representing a simple project of constructing one story conventional house [Fig. ***1***]. This adj. matrix is a weighted by activity durations. Initial durations are provided. CPM2 is CPM1+one noncritical activity added to it [Fig. ***3***]. CPM3 is CPM2 with one critical activity added [Fig. **4**]. CPM4 is CPM3 with a change in 7 edges location to correlate it with the Gantt produced by the project engineer [Fig. **6**]. CPM5 is CPM4 with one edge subtraction and a change in location of three edges to correlate it with the critical path produced by the project engineer [Fig. **7**].
Outdegree rank diagrams show rank distribution propagation downstream [Fig. **2**, Fig. **5**, Fig. ***8***] hinting repetitive formations.

<u>Rank</u> Power functions were fitted to outdegree of all cases, experiments and case-study alike [with a 95% confidence-Fig. **2**, Fig. **5**, Fig. ***8***, Fig. ***18***], thus confirming that all the networks are complex.
<u>Faults</u> Power function for CPM1,...,5 was produced in Fig. ***10***,
Risk log-normal **PDF** were matched [**Fig. *10***], - one fitting a construction project [such as case-studies 1-4] and one fitting an infrastructure facility [such as case-study5].
Decision rules for the experiment are, no correction for faults>threshold, and correction of all faults<threshold. Two thresholds were used: t>1, t>0.05
Experiments: application of all decision rules and STDV for each CPM1,…,5, for a growing number of iterations.

Results

Edges. The number of possible edges is n*(n-1) [Fig. **9**], where n is the number of nodes, that is, for CPM1,..,5 about 650 possible edges. In CPM1,..5 the actual number of edges is less than 1/6 [Fig. **9**]. Maximum number of spanning trees in a graph is n^{n-2} which, for CPM1 is in the magnitude of 10^{30} and for CPM2 10^{32}. Addition of one activity [CPM2 and CPM3] added 13, 21 possible routs [of added ~10^{32}, ~10^{34} possibilities respectively], whereas adjusting the edges [CPM4] added 47, and adjusting to the best practice by deleting an edge, added 3 'hidden' CP routs and subtracted 10 possible routes. This disparity between possible and actual numbers suggests the concept of viability kernel.
Rank power functions' When moving from CPM1➔CPM4 the power parameter abs(b) gets smaller while R^2 gets higher as the nodes and edges are added and also without adding to the network, when by changing location of edges, small world effect is enlarged, otherwise the direction reverses [Fig. 9].
Critical Path [CP] gets longer and/or alternative CP are progressively added [Fig. 9 bottom] When moving from CPM1➔CPM5.
Running the higher STDV related risk through CPM1 results in collapse of stability. The energy of faults with the **high STDV**, throw the network out of the attractors.
Entropy changes with iteration going to ever higher values.
Where **Ntropy** goes to 1 there is one definite CP [Fig. 14].
Criticality Index changes with iterations [Fig. 12], mirroring Entropy growth, new paths are found [Fig. **11**] and small morphological variation produce big behavioral changes [=butterfly effect, Fig. ***13***].
Attractors
Running the lower STDV risk produce **attractors** to the system [Fig. 14],
Fig. 9 presents all possible routes in a non-directed CPM1,..,5. The max-span-tree seems to coincide with the attractors [Fig. 14]. Fig. 13 shows that high STDV systems fined new attractors, not necessarily the max-span-trees. Fig. 15 shows that the system "chose" one of two max-span-trees and stayed within it. This robust outcome is a product of the decision rule and low energy faults' STDV.
Fig. 16 hints to modes of vibrations that "chose" the higher nodes in the eigenvectors, that is, the attractors are nodes not paths, Fig. 22 validates this suggestion.

Case-studies

On Appendix B, 5 case-studies were presented. In all cases a **DSM** matrix was generated, **Laplacian**, outdegree **Power function** [Fig. 18], a **P**rincipal **C**omponent **A**nalysis and some descriptive statistics.
<u>Case-study 1</u> C2012-13 Pumping Station Jabbeke, is a small project of adding control to a pumping station, timeline is short, - only 28 entries, and yet, there is a major collapse of CP.
<u>Case-study 2</u> C2011-13 Wind Farm DSM has 166 nodes and 120 documented time-intervals, that is, about 50,000 data entries. Yet, the network is rather simple, the rank low, the network is an emblem of concurrent engineering, and the buffers supporting the designated CP are numerous and large. Still, the CP collapses.

Case-study 3 is a model of good-practice. It is well planned and well managed. It is an in-situ synchronized, mostly linear production with no imported risk, hefty buffers on the non-critical paths, and a short timeline. The overall time overflow is negligible and yet the CP collapsed.
Case-study 4 present DSM of 16 hammock activities. Power function fitted to outdegree shows that the super network is complex. The system is rudimentary and small, yet CPM collapsed. Fig. 23 suggests that there are mistakes and omissions in the formation of the DSM and the model does not represent reality.
Case-study 5 presents a snapshot of a municipal stormwater drainage system. The network is complex, has paths, longest and alternative ones, and owing to the smaller STDV there are attractors.

Results

Imported Risk

Fig. ***18*** provides a snapshot of the divergence of the network, Fig. 19 presents imported risk. The upper graph shows that although duration of activities did not overflow, activities ran late, apparently for causes not incorporated in the project network. The lower graph shows that cost spikes with no correlation to time, tracing the origin of cost outside the production costs. It is evident that imported risk is overwhelming. Superposition of the blue graphs of Fig. 19 shows that cost spikes are independent of time latencies, exemplifying the phenomenon of power play (Yonat & Shohet, 2022). Fig. 18 shows that the network is not fixed, it evolves. Terminated activities are dead branches while new activities form a temporary network that is an ad-hoc manifestation of risk. CP changes within the network only because we, the viewers submit the picture of ad-hoc temporary networks to our model, thus integrating local nodes perturbations into an imaginary path that traverses the whole network that we conjure up.

Synchronization.

Fig. 20 shows that synchronization causes a correlated avalanche. This is a phenomenon of CPM networks, while common practice promotes synchronization.

Reification fallacy

Fig. 21 portrays a CPM network with a CP collapse while the project was not affected.

Redesign and coupled activities, Information networks

There are many rework loops on the network of a 2,3,4,5 order, such as “a4”-“a5”,”a4”-“a14”-“a15”, :a5”-“a10”-“a13”-“a15”-“a5”, some loops are random, mirroring (Eppinger & Browning, 2012) insight about inadequate presentation of coupled activities. The effects of higher order FB-loops are greater than those of lower order ones. Fig. 23 shows higher orders of coupling and E^4 Boolean cube showing that all activities from a4,..,a15 are coupled in the fourth degree. This means that every activity is revisited, and the network is iterated ad-infintum, yet, evidently, the project itself reached an ending.

Infrastructure facilities- a topological similarity.

The network representation of projects and infrastructure systems are topologically identical [Fig. 14]. There is a different meaning to the network’s constituents and outcome. Edges are conduits, nodes are junctions such as manholes, wights represent capacity or flow calculated by Bernoulli equation. The longest path duration determines the time for full capacity, coupled activities may produce a loop, hydraulic-jump, backwash.
Fig. 24 shows a small section of the system where two local topographic recesses are seasonally flooded and act as a coupled tanks system, that is, they act as an oscillator.
The morphology shows similarity with the non-directed graph of the info-system. This is a product of an emergent trait in the stormwater system: water flow under pressure against the gradient.

FALSIFICATION

Possible explicatory parameter values are presented on Fig. 9 for the CPM1,…,5 cases.
Entropy may be ruled out as a parameter because it is dependent on iterations [Fig. 13].
Ntropy goes to 1 as number of iterations grows. With small energy STDV, and one max-span-tree, Ntropy may be 1 from start.
Span-trees are ruled out because critical paths are sorted out of span-trees by the PDF at random, therefore, the Criticality Index is the relevant parameter.
CI is ruled out because CI values are dependent on iterations [Fig. 12].
Variance generated from the Laplacian has some correlation with the paths, being thus of some relevance when the CP is relevant. But networks' Variance is a function of iteration, therefore can be ruled out [Fig. ***13***].
Eigenvalue variance [Fig. 9] calculated from the weighted Laplacian [$\mathfrak{L} * H$] is a function of iterations too.
Max-span-trees are usually referred to as "hidden" or **"alternative". CP** are relevant as attractors when STDV is small [Fig. ***15***]. Their relevance is incidental as emanates from the following discussion on vibration modes and Fig. 14. Still, CP may be useful as portrayed on case-study 5. The attractors are [statistically] correlated with max-span trees, therefore with CI and Entropy.
Max-span-trees were falsified as explicatory parameters in Fig. 13.
Rank by itself has no explicatory value. Imagine a graph that starts from a node, has an edge to all other nodes but the last, and all these nodes are connected by an edge to the last. As the number of middle nodes rises, the rank rises, entropy rises and yet criticality index is decided by the initial weight of the nodes and the stdv.
Power function "b"
Morphology power function is an indication of Small World.
Faults power function is a trait of the system thus an indication to the general behavior of the system. This can be used to suggest the market segment of the project and to find avalanched systems (Yonat & Shohet, 2022).
Higher abs(b) are related to stabler attractors,
Power function "b" is useful when monitored throughout the project lifespan to indicate change.
Simulations
CPM systems cannot solve networks with loops.
To address this, simulations have been suggested in the literature (Abdelsalam & Bao, 2006).
Simulations are prone to reification difficulties and their outcome is dependent on morphology (Malyusz et al., 2021).
The above presentation rules out Simulations as a tool to predict CP.
Replicator function
On Fig. 20 a part of the diag(L*H) vector for the first few xi is incorporated.
There is no justification for the difference between the first few x_i, the first nodes are all in one line, they may be swapped or correlated with no effect on the CP. This outcome falsifies Equation 4 and Equation 5.
Eigen-ratio and Eigen-variance can be ruled out directly from Fig. 9, for CPM2 is no stabler than CPM1.
Vibration modes
In the numerical experiment, the modes of vibration are attracted to the most vibrant nodes [Fig. 16], the same results are presented in case-study 3 [Fig. 22]. Networks morphologies unfold randomly in time, configures new networks as they are produced falling into attractors that are not lines, but rather nodes.

Vibration modes are represented by eigenvectors spectrum and their refraction modes. This is the only morphological explicatory parameter [Fig. 22] found in this research.

DISCUSSION

The smallest possible morphological variations are dictated by the discrete nature of the network. Adding a node, a subtraction of an edge or the changing of an edge location. The viability kernel is small relatively to the number of possible edges, yet big enough to enable various alternatives, the recurrence of recursive repetitive formations, small world, and much room for skill (Eppinger & Browning, 2012). Owing to the complex nature of the network, it is impossible to predict the effect of a variation.

It is evident, though, that changing CPM3 to CPM4,5 to give it teleonomic coherence enhanced Small World effects and synchronization. Is this outcome a general tendency? Can it be safely assumed that well planned projects are more stable? If this is the case, then the CPM model stability goes down [Fig. 14] while actual project stability goes up [Fig. 22].

CPM networks do not represent well complex systems. A failed CP network does not imply a failed project [case-study 4], stability loss implies that the locus of CP changes and not necessarily that time/cost goals are compromised.

Synchronization is promoted because it reduces complexity. A fixed process with synchronized lines of production is an industrial line of production, activities are performed by robots and CNC, autonomous agents who are causes of chaos are eliminated. This is another discrepancy between CPM models and reality [case-study 2]. The destructive effects of unsynchronized activities are mathematically produced in (Yonat & Shohet, 2022).

CPM Systems are prone to miss-representation owing to modeling mistakes [Fig. 23], such as modeling activities rather than information [Fig. 23], modeling difficulties generated by coupling [Fig. 24], imported risk and constraints [Fig. 19], redesign [Fig. 23], and networks' stochastic evolving [Fig. 18], to this the statistics of perturbations is added [Fig. 10] and the complex modes of response of the system [Fig. 13].

Wherever there is a physical link between activities, there is an information one. The opposite sentence is not correct. Moreover, information edges are not directed while CPM networks are directed. CPM networks fail to represent information networks and therefore, information caused effects on time [case-study 4].

In actual systems, faults cause avalanche (Yonat & Shohet, 2022). In CPM models a delay propagates without the Fibonacci effect on magnitude.

Faults Multiplication and propagation and correlated avalanche is generated via information links, physical contiguities of the building, supply chain and design edges that are not accounted for in CPM.

Case-study 3 exemplifies a Reification fallacy. The network does not represent the project. There is no collapse in the project itself and being thrown out of the attractor did not affect the success of the project. This reification fallacy is exemplified by CPM3,..5 which are all viable networks for the same project and none of them represent a real project correctly. Nets' nodes, edges and durations, constraints and resources representation are not true to reality.

ToF suggestion that the relevant statistics is open faults' statistics, and the relevant morphology is the **info-system's** morphology is sustained by Fig. 23. In Fig. 23 it is evident that the network presented is an information network, information is what flows through the coupled [rework] edges.

Off-site production such as precast and industrial ready-made elements is of lower STDV, this causes higher on-site variance. This phenomenon is manifested on Fig. 19, Fig. 20 and the contrary effect of concurrent in-situ production on Fig. 21. A mathematical explanation is that the integral of risk is one, thus, when offsite elements are of lower STDV, the risk left to site operations is higher. This is a product of morphology [the degree of the system is higher, there are an addition of networks with subsets of modular hierarchies], of time management [contradicting schedules], of production [mismatch of production tolerances], of opposing interests [independent agents having diverse interests], and most notably in this research, of design,- design becomes part of the production process introducing rework loops [Fig. 23].

Evolutionary graph theory is not applicable. The formulation is inadequate to sustain it. The CPM generated replicator Equation (4) does not have a forecasting capacity.

The explicatory mathematical tools [Fig. 9] were falsified. This calls for the development of means that have reliable effects under complexity.

When developing a model, a network is constructed, and the computer software finds the longest path in it. This path is bound to fail as CP. Praxis suggests the design of production line, and that line is to be set as the CP. The management of CP is not a management of a software generated longest path, but rather, it is the management of a production sequence of serial standardized repetitive production lines with constant production frequency. This is the morphological side of the solution. For the PDF side, the management of faults is treated on (Yonat & Shohet, 2022).

In this scenario CPM are used in the planning process to weed-out long paths. For this purpose, **Minimum networks** must be produced using Invariance content and modular hierarchies [using dimensionality reduction, topological identities, minimum teleonomic information], constraints and supply chain should be explicitly presented. There is a venue for a use of CPM also in the project management process to simulate the possible long-paths emanating of the stochastic evolving networks [Fig. 18].

In infrastructure facilities the attractors are used for prediction of emergent responses and for management of the system in real time and for system development and redesign [case-study 5].

There are natural systems that harness complexity [SOC- self adjusting criticality], such as the brain neuronal emission. Is there a possibility for a managerial heuristic that follows this path? Praxis suggests the affirmative. [plan for regularity, repetition, and chance (Monod, 1971)].

The hypothesis that stability of networks is determined by statistics and morphology was amply validated throughout the article, the strong statement that only statistics and morphology are the determining factors is left for further research.

SAMMARY and CONCLUSIONS

CPM systems are inherently unstable under complex **Morphology**.

Added to it, is the destabilizing **Faults' PDF**, generating a complex system response. Subjected to the risk relevant to construction projects, all networks generated in the experiments and case-studies lost stability.

CPM networks are ill-equipped for presenting the actual systems, causing a **Reification bias**.

The instability of the networks was presented by variations in **C**ritical **P**ath and **C**riticality **I**ndex. Traits of **complexity** such as the butterfly effect were manifested when minor modifications in morphology and risk caused unpredictable outcome, and emergent traits such as the formation of oscillators surfaced.

The role of **imported risk** was found to be major. This risk is external to the network and its influence on stability was catastrophic. On the contrary end, synchronization, which is a network morphological [internal] trait manifested by coupling and **loops**, had catastrophic effects on network stability.

Entropy was found to be dependent on iterations. This outcome was by itself sufficient to falsify all the tested stability parameters such as Criticality Index, eigen-ratio variance, and other morphological and statistical parameters and to establish that replicator equations lose their predictive capacity. The only explicatory parameter that was not falsified, is the eigen-spectral refraction.

Eigen-spectral refraction directed attention to **attractors**.

It was established that attractors are nodes rather that paths.
CPM networks were used to suggest attractors for systems of low faults' STDV such as infrastructure facilities.
Praxis suggests project management that is directed towards coherence, synchronization, and small world effects. These directives, that promote the stability of projects, generate contrary effects in CPM networks.
The **P**roject **M**anagement practice of design of concurrent production sequences that are set as the Critical Path is recommended. CPM co-employed with eigen-refraction is suggested to weed out alternative critical paths in projects, and to indicate possible attractors in infrastructure. There is one major correction to the CPM model that is needed to enable its use,- the networks that should be used are information networks. Information networks have feedback loops, rework processes, modular recursive formations of sub-networks and constraints. These attributes are not well resolved by CPM. To enable CPM and usefulness, networks must be **Minimum Networks**.
The contribution of this research is the falsification of current CPM tools and explicatory parameters, proving established paradigm and systems to cause reification fallacy. From this finding emanates the suggestion to return to Good-Practice engineering of project management, rather than networks management.

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Appendix A- Numerical experiments

[3] Sagie J.A. engineering and Construction LTD

CPM1

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	duration
ground works	1	1	1			1																				1
foundations	2		1	1																						1
base	3			1	1		1	1						1				1		1						1
electricl inst	4				1						1	1	1	1	1	1	1									1
instlation	5					1		1	1		1		1				1									1
piers	6						1	1	1																	1
walls	7							1		1	1															1
ceiling	8								1	1	1	1									1	1				1
plaster	9									1		1					1									1
flooring	10										1						1									1
Air conditioning	11											1				1										1
kitchen	12												1				1						1			1
communication	13													1		1										1
security	14														1	1										1
control	15															1								1		1
paint	16																1						1	1		1
instalation outdoors	17																	1	1	1						1
plaster outwalls	18																		1	1						1
development	19																			1	1					1
gardening	20																				1			1		1
isoltion	21																					1	1			1
sanitary instalations	22																						1		1	1
electrical instalations	23																							1	1	1
Delivery	24																								1	1
Max		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	24

Fig. 1. CPM1 Adjacency matrix

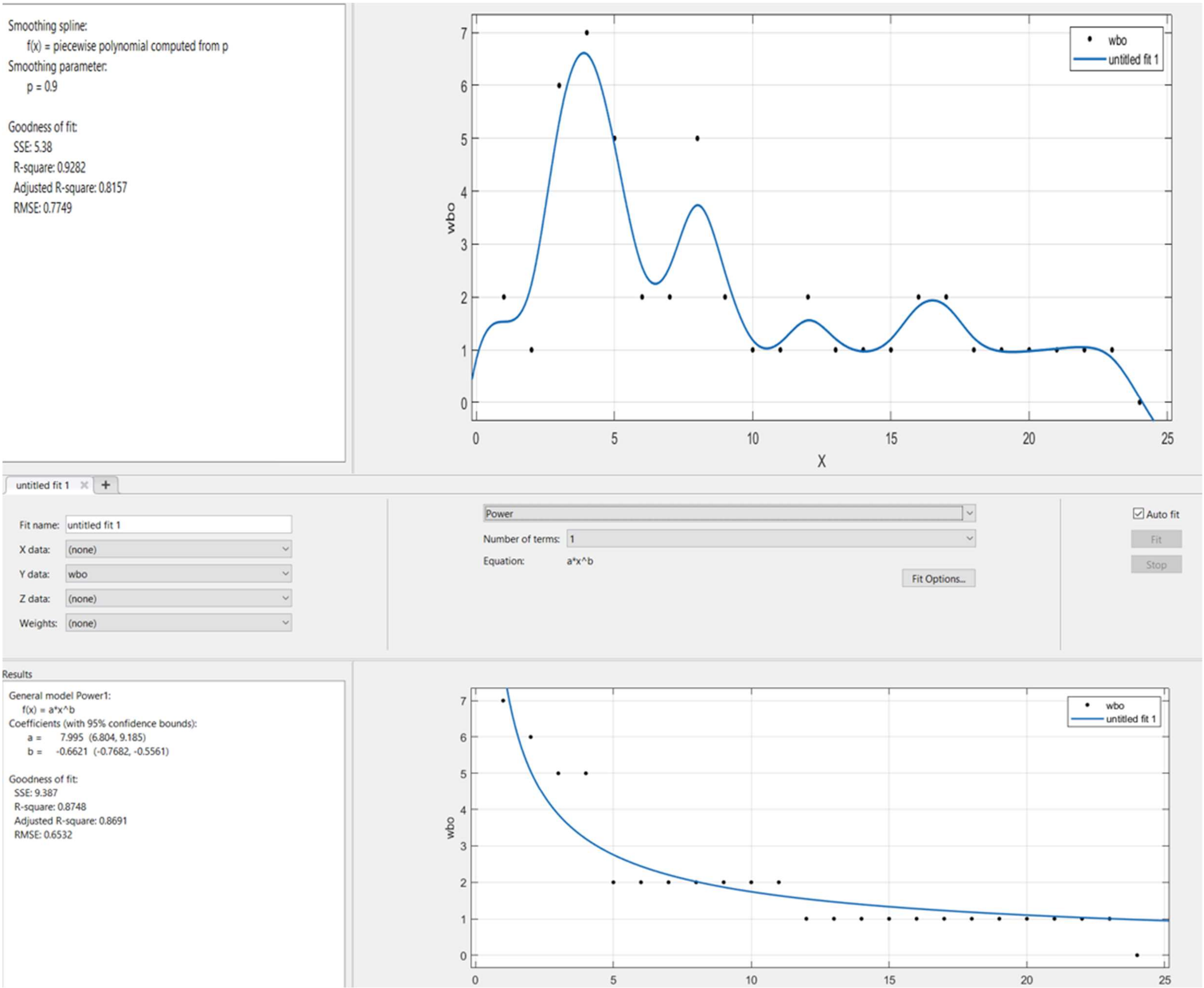


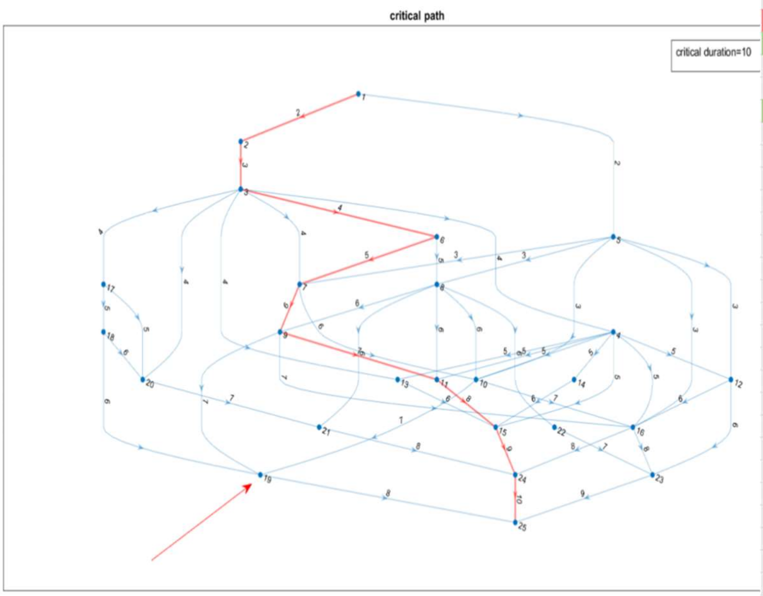
Fig. 2. CPM1 Outdegree Rank [wbo] graph v/s/ node numbers and power function who vs. cumulative number of nodes.

CPM2

Is CPM 1 +activity 19 added [**Fig. *3***].

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	duration
ground works	1	1	1			1																					1
foundations	2		1	1																							1
base	3			1	1		1	1						1				1			1						1
electricl inst	4				1						1	1	1	1	1	1	1										1
instlation	5					1		1	1		1		1				1										1
piers	6						1	1	1																		1
walls	7							1		1	1																1
ceiling	8								1	1	1	1										1	1				1
plaster	9									1		1					1			1							1
flooring	10										1						1			1							1
Air conditioning	11											1				1											1
kitchen	12												1				1							1			1
communication	13													1		1											1
security	14														1	1											1
control	15															1									1		1
paint	16																1							1	1		1
instalation outdoors	17																	1	1		1						1
plaster outwalls	18																		1	1	1						1
Aluminium instalation	19																			1						1	1
development	20																				1	1					1
gardening	21																					1			1		1
isoltion	22																						1	1			1
sanitary instalations	23																							1		1	1
electrical instalation	24																								1	1	1
Delivery	25																									1	1

trace (lplc)=	106
maxRank=	8
avarageRank=	4.2



Laplacian full

																									eigenvalues{
2	-1	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-1	2	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.840078
0	-1	7	-1	0	-1	-1	0	0	0	0	0	-1	0	0	0	-1	0	0	-1	0	0	0	0	0	0.9374339
0	0	-1	8	0	0	0	0	0	-1	-1	-1	-1	-1	-1	-1	0	0	0	0	0	0	0	0	0	1.1526831
-1	0	0	0	6	0	-1	-1	0	-1	0	-1	0	0	0	-1	0	0	0	0	0	0	0	0	0	1.7319905
0	0	-1	0	0	3	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.8322978
0	0	-1	0	-1	-1	5	0	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.107711
0	0	0	0	-1	-1	0	7	-1	-1	-1	0	0	0	0	0	0	0	0	0	-1	-1	0	0	0	2.3919222
0	0	0	0	0	0	-1	-1	5	0	-1	0	0	0	0	-1	0	0	-1	0	0	0	0	0	0	2.5344322
0	0	0	-1	-1	0	-1	-1	0	6	0	0	0	0	0	-1	0	0	-1	0	0	0	0	0	0	2.7146815
0	0	0	-1	0	0	0	-1	-1	0	4	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	2.997796
0	0	0	-1	-1	0	0	0	0	0	0	4	0	0	0	-1	0	0	0	0	0	0	-1	0	0	3.5163656
0	0	-1	-1	0	0	0	0	0	0	0	0	3	0	-1	0	0	0	0	0	0	0	0	0	0	3.981837
0	0	0	-1	0	0	0	0	0	0	0	0	0	2	-1	0	0	0	0	0	0	0	0	0	0	4.1613158
0	0	0	-1	0	0	0	0	0	0	-1	0	-1	-1	5	0	0	0	0	0	0	0	0	-1	0	4.8526581
0	0	0	-1	-1	0	0	0	-1	-1	0	-1	0	0	0	7	0	0	0	0	0	0	-1	-1	0	5.0528096
0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	3	-1	0	-1	0	0	0	0	0	5.2409965
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	3	-1	-1	0	0	0	0	0	5.5185629
0	0	0	0	0	0	0	0	-1	-1	0	0	0	0	0	0	0	-1	4	0	0	0	0	0	-1	5.9342896
0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	-1	0	4	-1	0	0	0	0	6.5516779
0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	-1	3	0	0	-1	0	6.9982411
0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	2	-1	0	0	7.7513334
0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	-1	0	0	0	0	0	-1	4	0	-1	8.1143787
0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	-1	0	0	0	0	-1	0	0	4	-1	9.3220231
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	-1	-1	3	9.7624843
																					eigenratio			$\frac{\theta_{max}}{\theta_1}=$	11.620926

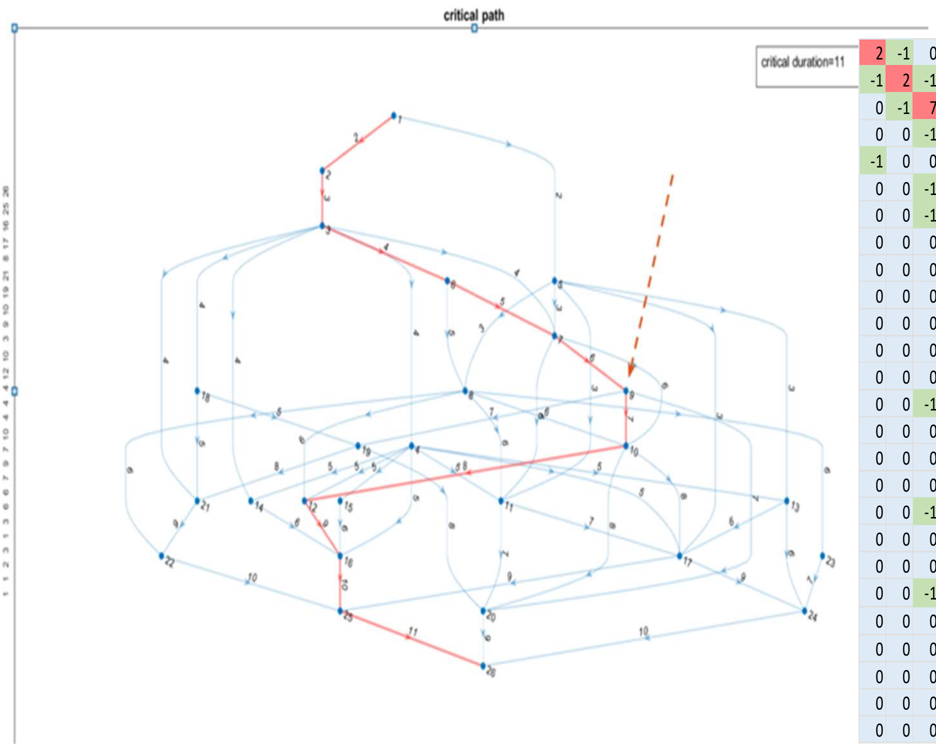
Fig. 3. CPM2 Adjacency matrix, Laplacian and network with CP and added node location

CPM3

Is CPM 2 +activity 9 added [Fig. 4].

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	
ground works	1	1	1			1																						1
foundations	2		1	1																								1
base	3			1	1		1	1							1				1			1						1
electricl inst	4				1							1	1	1	1	1	1	1										1
instlation	5					1		1	1			1		1				1										1
piers	6						1	1	1																			1
walls	7							1		1	1	1																1
ceiling	8								1		1	1	1										1	1				1
Auxiliary frames	9									1	1									1	1							1
plaster	10										1		1					1			1							1
flooring	11											1						1			1							1
Air conditioning	12												1				1											1
kitchen	13													1				1							1			1
communication	14														1		1											1
security	15															1	1											1
control	16																1									1		1
paint	17																	1							1	1		1
instalation outdo	18																		1	1		1						1
plaster outwalls	19																			1	1	1						1
Aluminium instalati	20																				1						1	1
development	21																					1	1					1
gardening	22																						1			1		1
isoltion	23																							1	1			1
sanitary instalatic	24																								1		1	1
electrical instalat	25																									1	1	1
Delivery	26																										1	1
Max		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	26

trace=	114
MaxRank=	8
Average(rank)=	4



2	-1	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-1	2	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	-1	7	-1	0	-1	-1	0	0	0	0	0	0	-1	0	0	0	-1	0	0	-1	0	0	0	0	0
0	0	-1	8	0	0	0	0	0	0	-1	-1	-1	-1	-1	-1	-1	0	0	0	0	0	0	0	0	0
-1	0	0	0	6	0	-1	-1	0	0	-1	0	-1	0	0	0	-1	0	0	0	0	0	0	0	0	0
0	0	-1	0	0	3	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	-1	0	-1	-1	6	0	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	-1	-1	0	7	0	-1	-1	-1	0	0	0	0	0	0	0	0	0	-1	-1	0	0	0
0	0	0	0	0	0	-1	0	4	-1	0	0	0	0	0	0	0	0	-1	-1	0	0	0	0	0	0
0	0	0	0	0	0	-1	-1	-1	6	0	-1	0	0	0	0	-1	0	0	-1	0	0	0	0	0	0
0	0	0	-1	-1	0	-1	-1	0	0	6	0	0	0	0	0	-1	0	0	-1	0	0	0	0	0	0
0	0	0	-1	0	0	0	-1	0	-1	0	4	0	0	0	-1	0	0	0	0	0	0	0	0	0	0
0	0	0	-1	-1	0	0	0	0	0	0	0	4	0	0	0	-1	0	0	0	0	0	0	-1	0	0
0	0	-1	-1	0	0	0	0	0	0	0	0	0	3	0	-1	0	0	0	0	0	0	0	0	0	0
0	0	0	-1	0	0	0	0	0	0	0	0	0	0	2	-1	0	0	0	0	0	0	0	0	0	0
0	0	0	-1	0	0	0	0	0	0	0	-1	0	-1	-1	5	0	0	0	0	0	0	0	0	-1	0
0	0	0	-1	-1	0	0	0	0	-1	-1	0	-1	0	0	0	7	0	0	0	0	0	0	-1	-1	0
0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	-1	0	-1	0	0	0	0	0
0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	-1	4	-1	-1	0	0	0	0	0
0	0	0	0	0	0	0	0	-1	-1	-1	0	0	0	0	0	0	0	-1	5	0	0	0	0	0	-1
0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	-1	0	4	-1	0	0	0	0
0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	-1	3	0	0	-1	0
0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	-1	0	0
0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	-1	0	0	0	0	0	-1	4	0	-1
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	-1	0	0	0	0	-1	0	0	4	-1
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	-1	-1	3

Fig. 4. CPM3 Adj. Matrix, Laplacian, and network with location of added activity on the CP

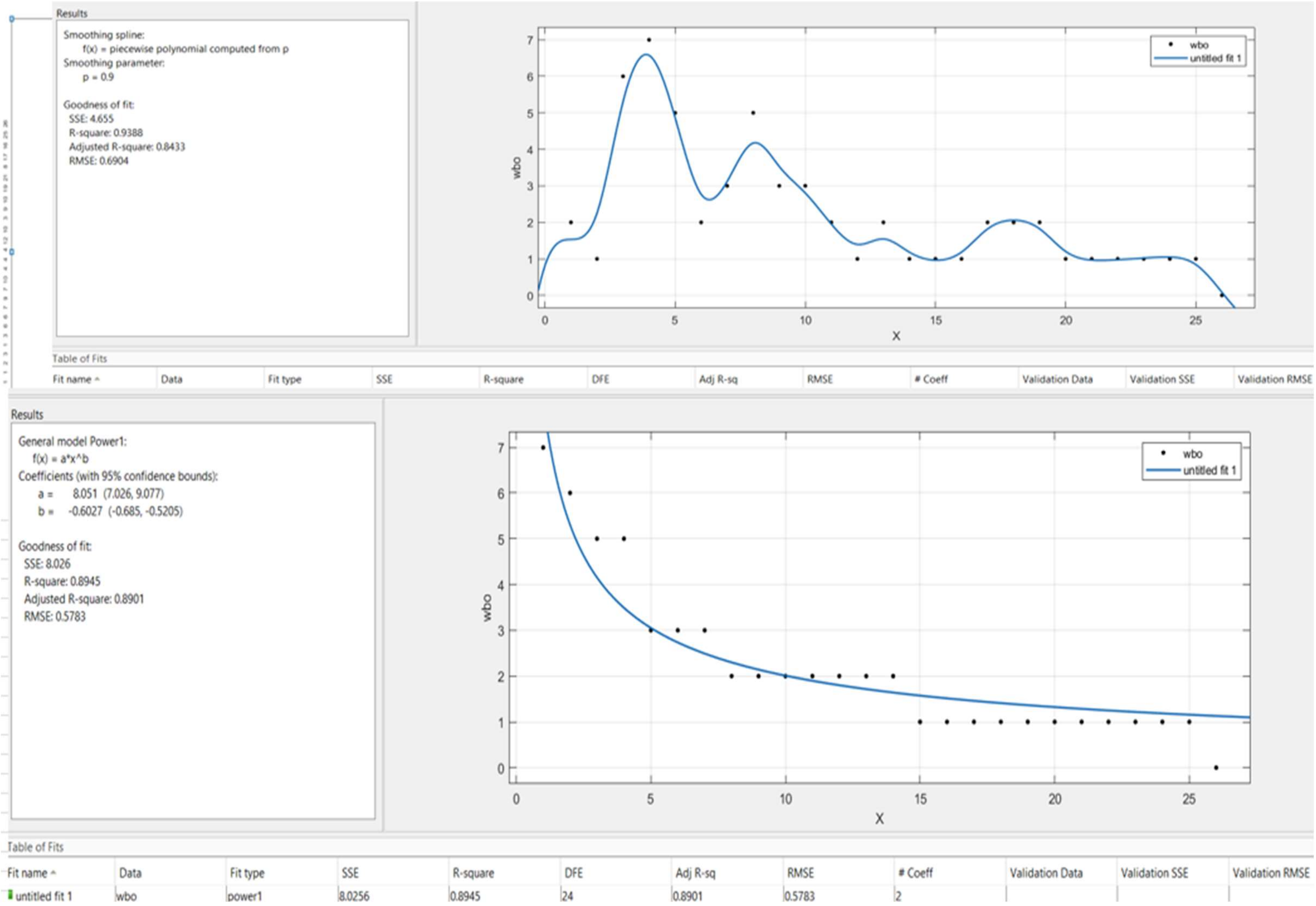


Fig. 5. CPM3 Outdegree nodes rank graph and power function

CPM4

Is CPM 3 +a change in location of node, there is no addition/subtraction of nodes or edges [**Fig. 6**].

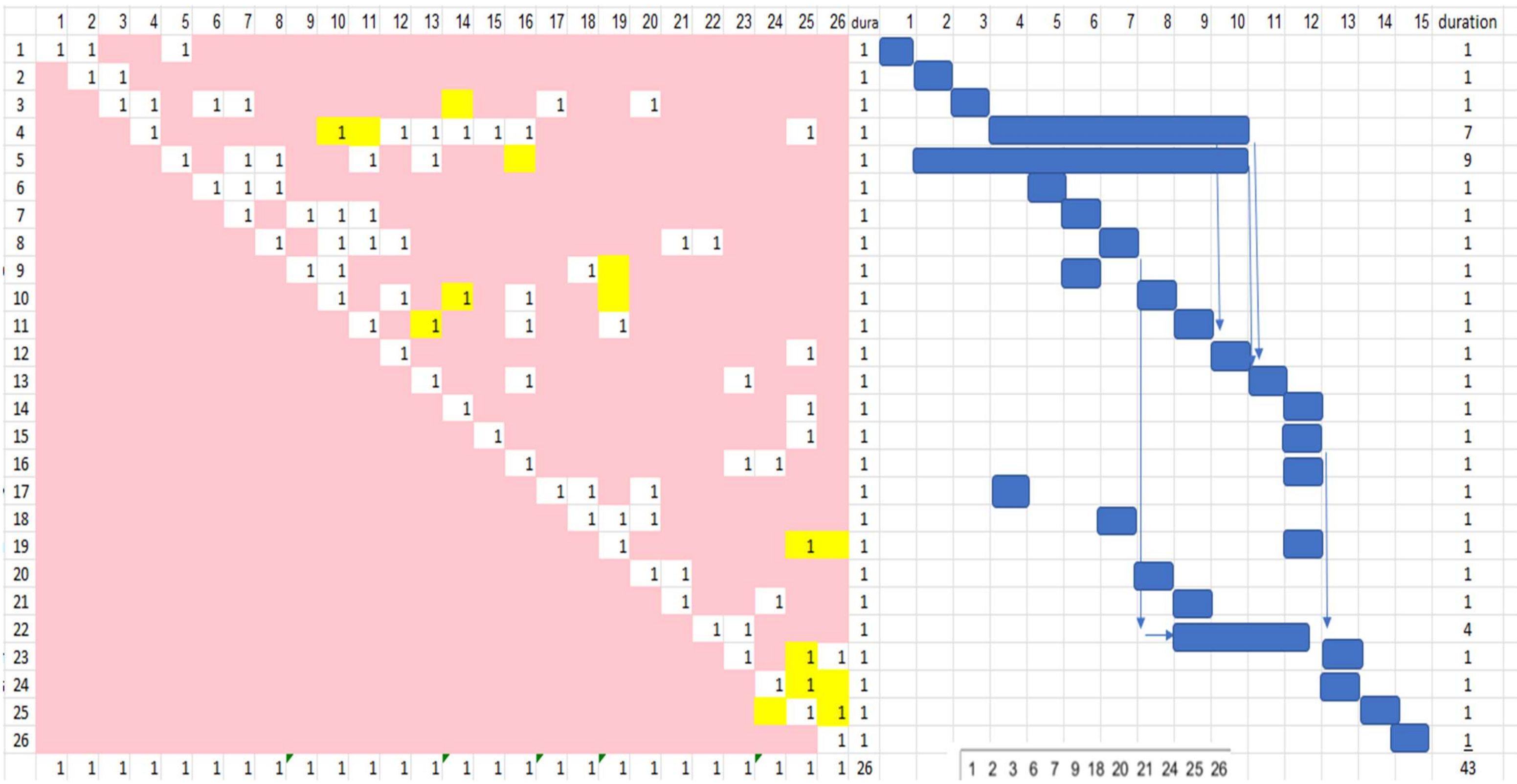


Fig. 6. CPM4 Adj. Mtx and Gantt

CPM5

Is CPM4 +with a change in location of three edges + one edge deleted [**Fig. *3***].

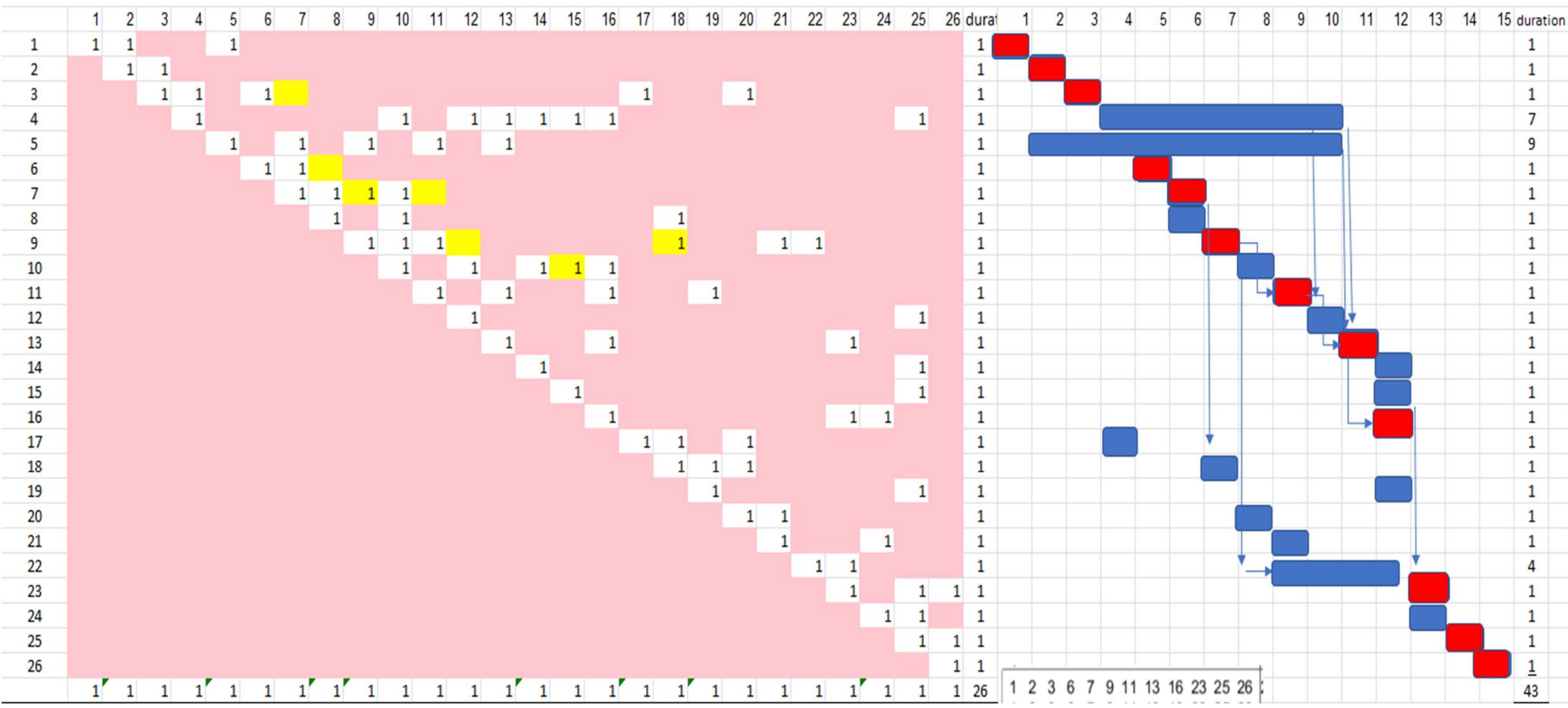


Fig. 7. CPM5 Adj. Matrix, and Gantt with Critical Path

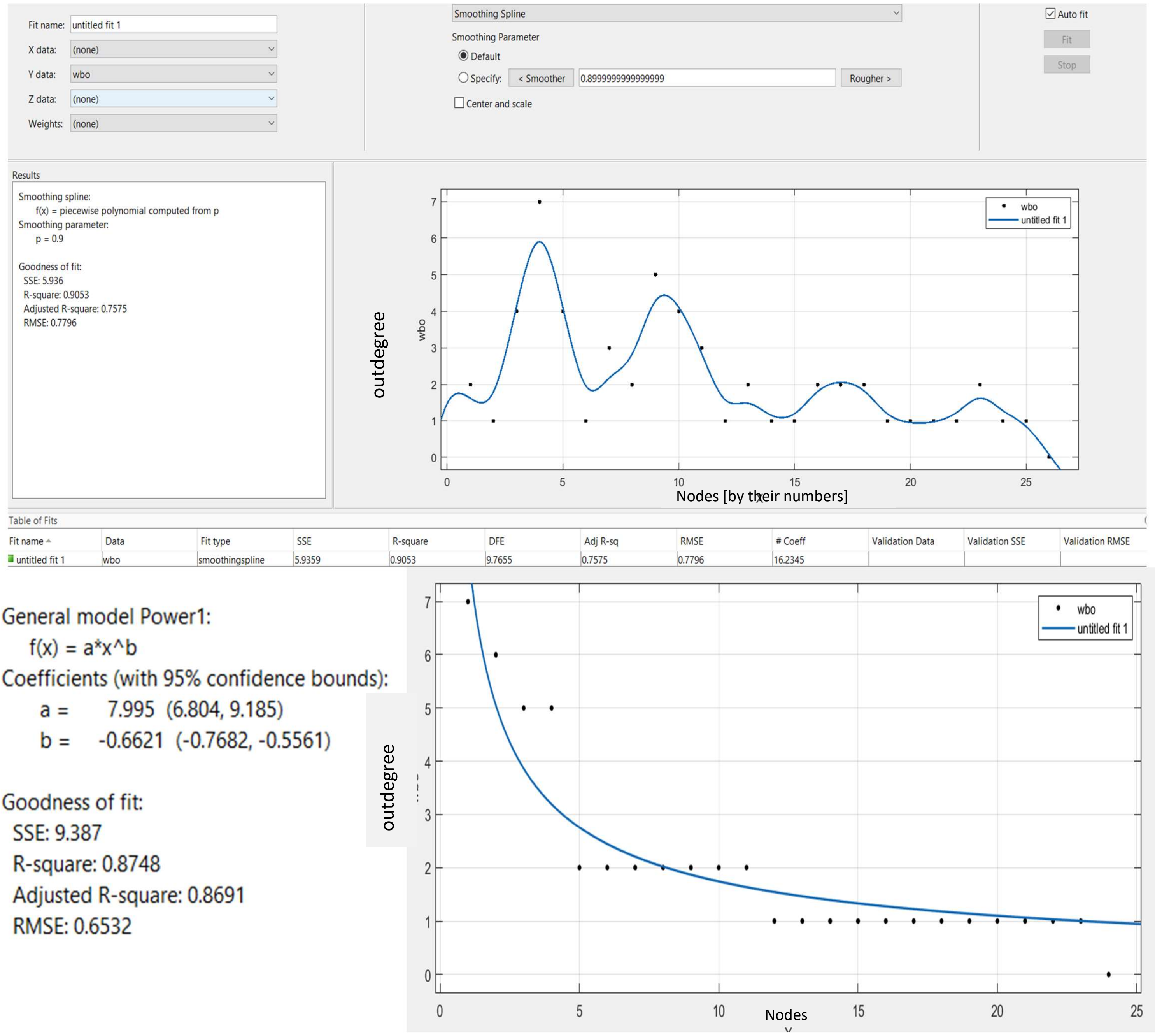
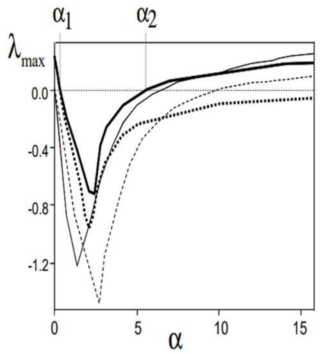


Fig. 8. CPM5 Outdegree nodes rank graph and power function

Laplacian CPM	CPM1	CPM2	CPM3	CPM4	CPM5		
Nodes	24	25	26	26	26		
trace laplacian	98	106	114	112	110		
CPM edges	49	53	57	56	55		
n*(n-1)=	552	600	650	650	650		
average(Rank)	4.08	4.24	4.38	4.31	4.23		
Max(Rank)	8.00	8.00	8.00	8.00	8.00		
trace Laplacian	98	106	114	114	110		
minspantree	5	5	5	4	4		
allspantrees	53	66	87	134	124		
averagespatree	7.60	7.45	7.76	8.45	8.47		
R^2	0.875	0.887	0.895	0.916	0.875		
abs(b)	0.662	0.630	0.603	0.585	0.662		
Entropy.33	0.1414	0.3251	0.3251	0.3258	0.3251	σ=	0.33
Entropy.99	1.2162	2.1965	2.1965	1.7268	1.7268	σ=	0.99
Ntropy.33	0.204	0.469	0.469	0.470	0.469	σ=	0.33
Ntropy.99	0.679	0.954	0.954	0.887	0.8874	σ=	0.99
σ_θ^2=	0.463	0.418	0.400	0.443	0.4573	σ=	0.33
$\frac{\theta_{max}}{\theta_1}$= eigenratio	16.04	11.62	11.54	13.45	14.408	σ=	0.33
var(eigenvalue)	7.72	7.52	7.69	8.22	8.1846		
var(lplcn)			27.68		26.8		

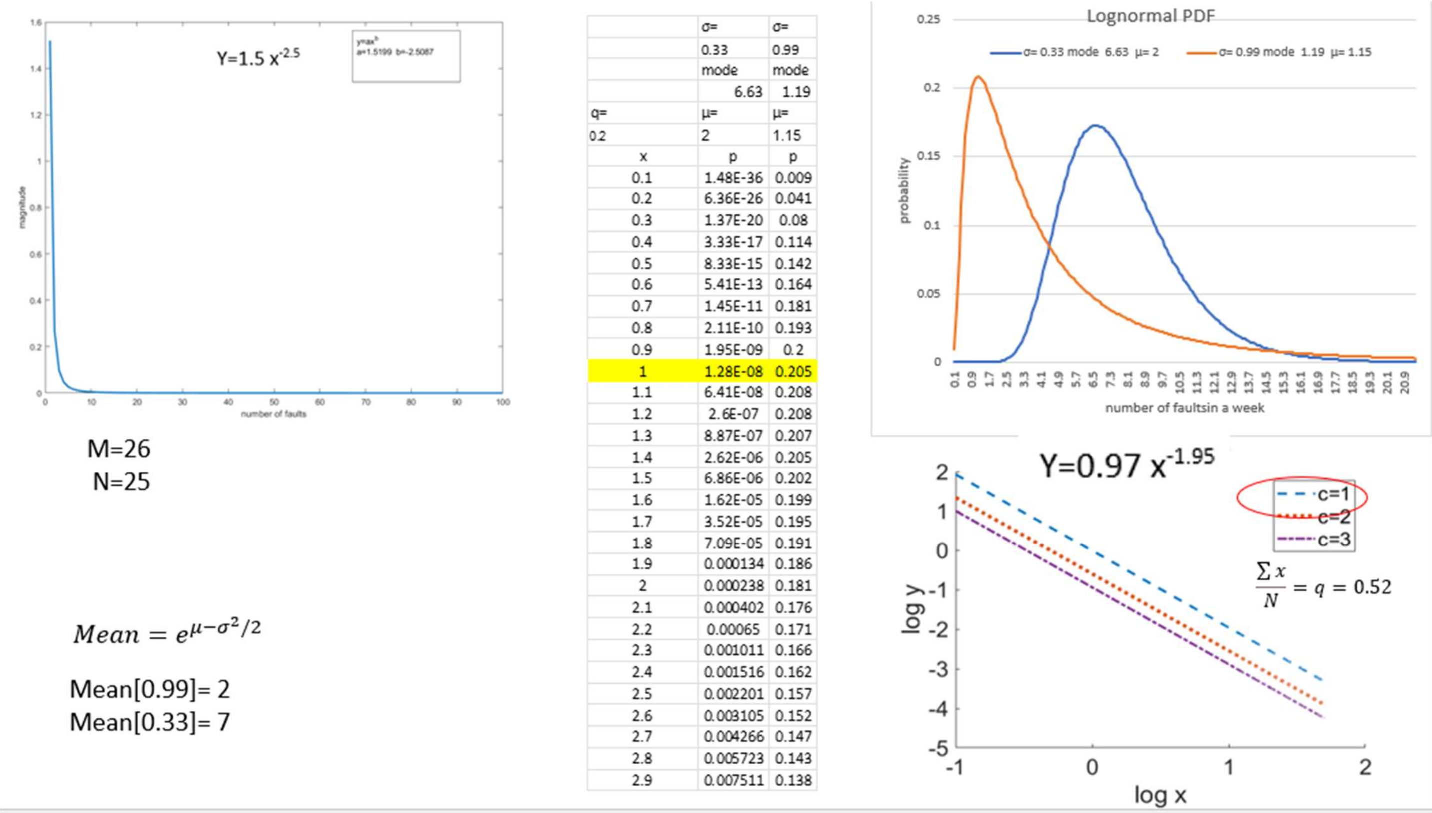


$$\theta_{\max}/\theta_1 < \alpha_2/\alpha_1 \equiv \beta,$$

$$\sigma_\mu^2 = \frac{1}{d^2(N-1)} \sum_{i=2}^{N} |\mu_i - \bar{\mu}|^2,$$

maxspantree	12	11	10	9	8	7	6	5
CPM			2	11	16	15	6	3
CPM2			2	11	20	19	10	4
CPM3		2	6	17	25	22	11	4
CPM4	1	7	22	35	35	25	8	1
CPM5	4	8	22	21	31	30	7	1

Fig. 9. explicatory parameters for CPM1,…,5



	σ=	σ=
	0.33	0.99
	mode	mode
	6.63	1.19
q=	μ=	μ=
0.2	2	1.15
x	p	p
0.1	1.48E-36	0.009
0.2	6.36E-26	0.041
0.3	1.37E-20	0.08
0.4	3.33E-17	0.114
0.5	8.33E-15	0.142
0.6	5.41E-13	0.164
0.7	1.45E-11	0.181
0.8	2.11E-10	0.193
0.9	1.95E-09	0.2
1	1.28E-08	0.205
1.1	6.41E-08	0.208
1.2	2.6E-07	0.208
1.3	8.87E-07	0.207
1.4	2.62E-06	0.205
1.5	6.86E-06	0.202
1.6	1.62E-05	0.199
1.7	3.52E-05	0.195
1.8	7.09E-05	0.191
1.9	0.000134	0.186
2	0.000238	0.181
2.1	0.000402	0.176
2.2	0.00065	0.171
2.3	0.001011	0.166
2.4	0.001516	0.162
2.5	0.002201	0.157
2.6	0.003105	0.152
2.7	0.004266	0.147
2.8	0.005723	0.143
2.9	0.007511	0.138

Fig. 10. Statistics of open Faults generation

The mathematic procedure (Yonat & Shohet, 2022) yielded the power function presented on **Fig. 11**. The procedure used in (Yonat & Shohet, 2022) works well for data presented in the literature but "overshoots" when actual number of faults is used. A simple project of the like of CPM5 does not merit b>2. For the numerical experiment, the log-log graph of **Fig. *10*** was used. This graph was produced for "q" generated from data provided in the literature. It fits better projects of the like, it is lower and has lesser effect, therefore, it depresses the effects of perturbations.

stability

σ= 0.99
μ= 1.15

CPM1

Model: an irreversible process for t>1

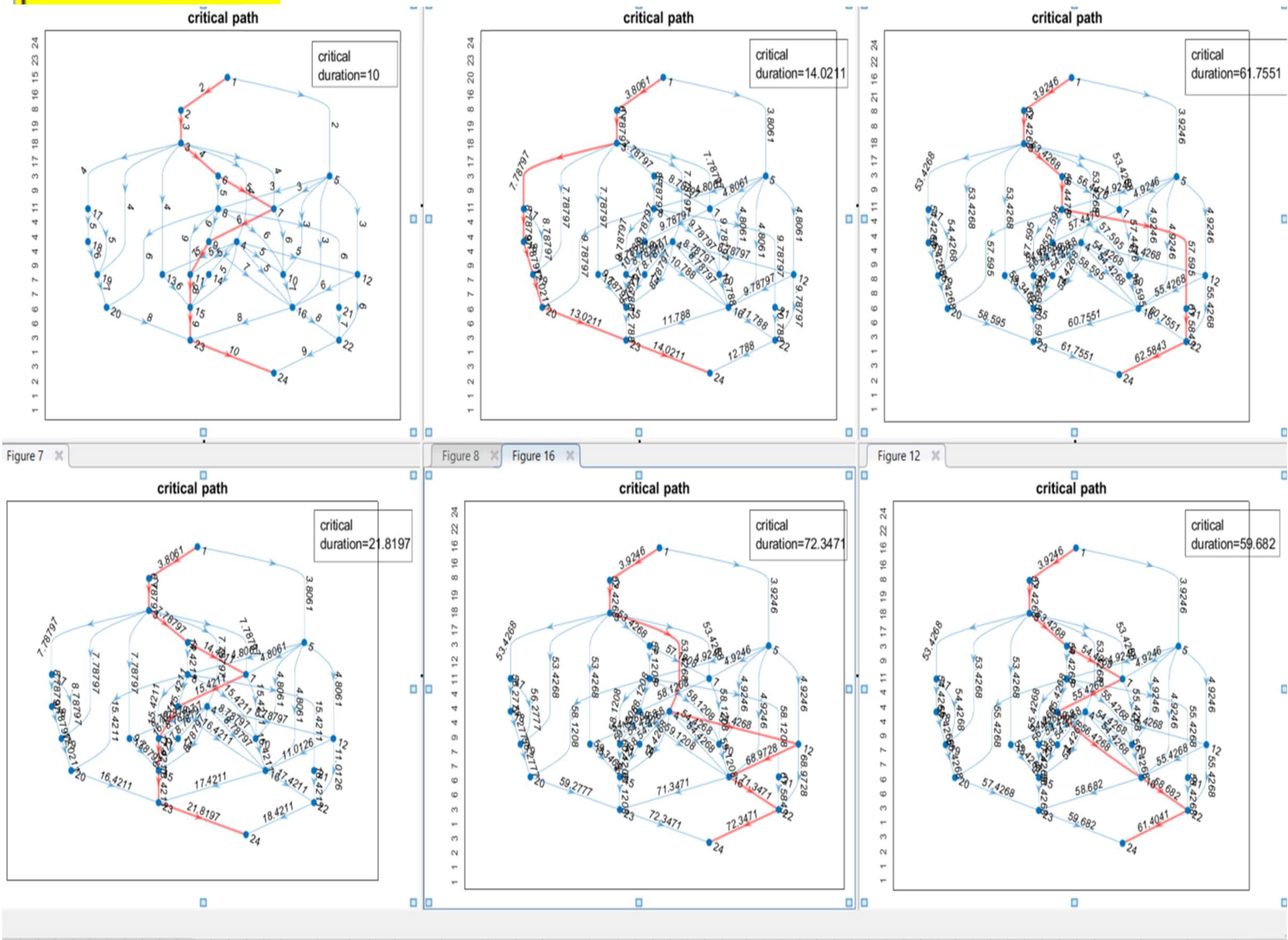


Fig. 11. CPM1 CP changes with iterations

Criticality index

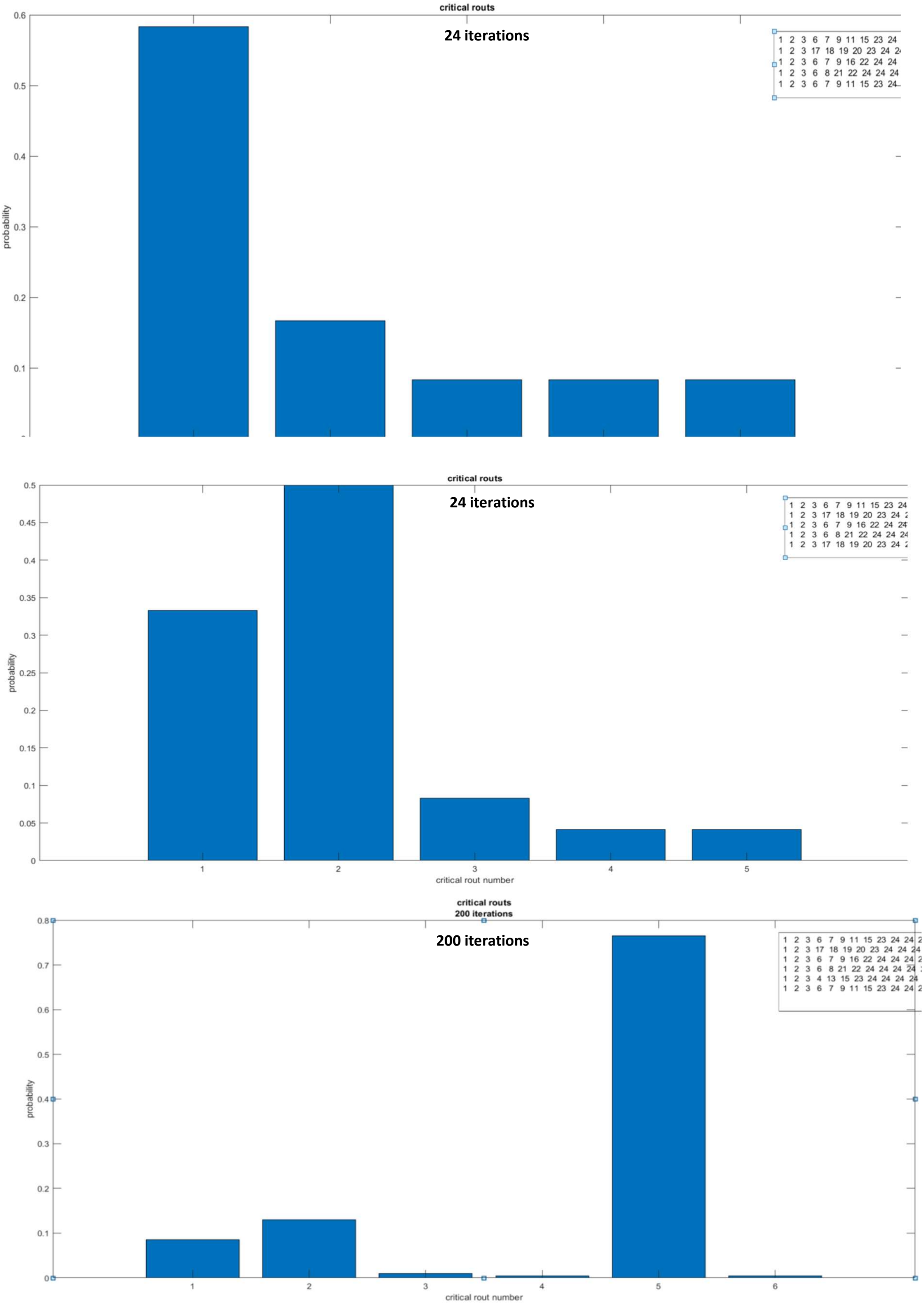


Fig. 12. CPM1 criticality Index variations with iterations

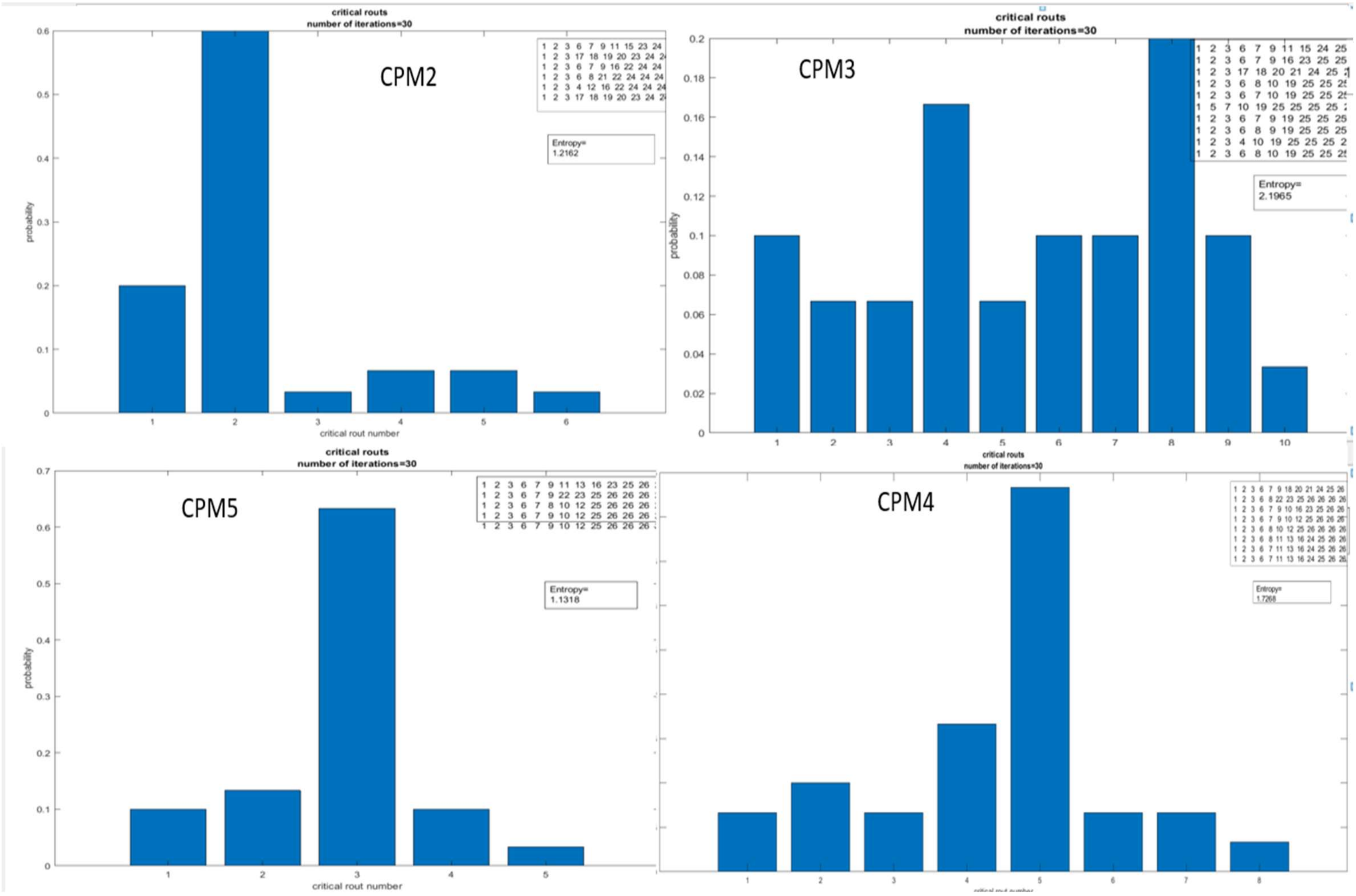


Fig. 13. CI for systems CPM2,…,5 after iterations

Nntropy

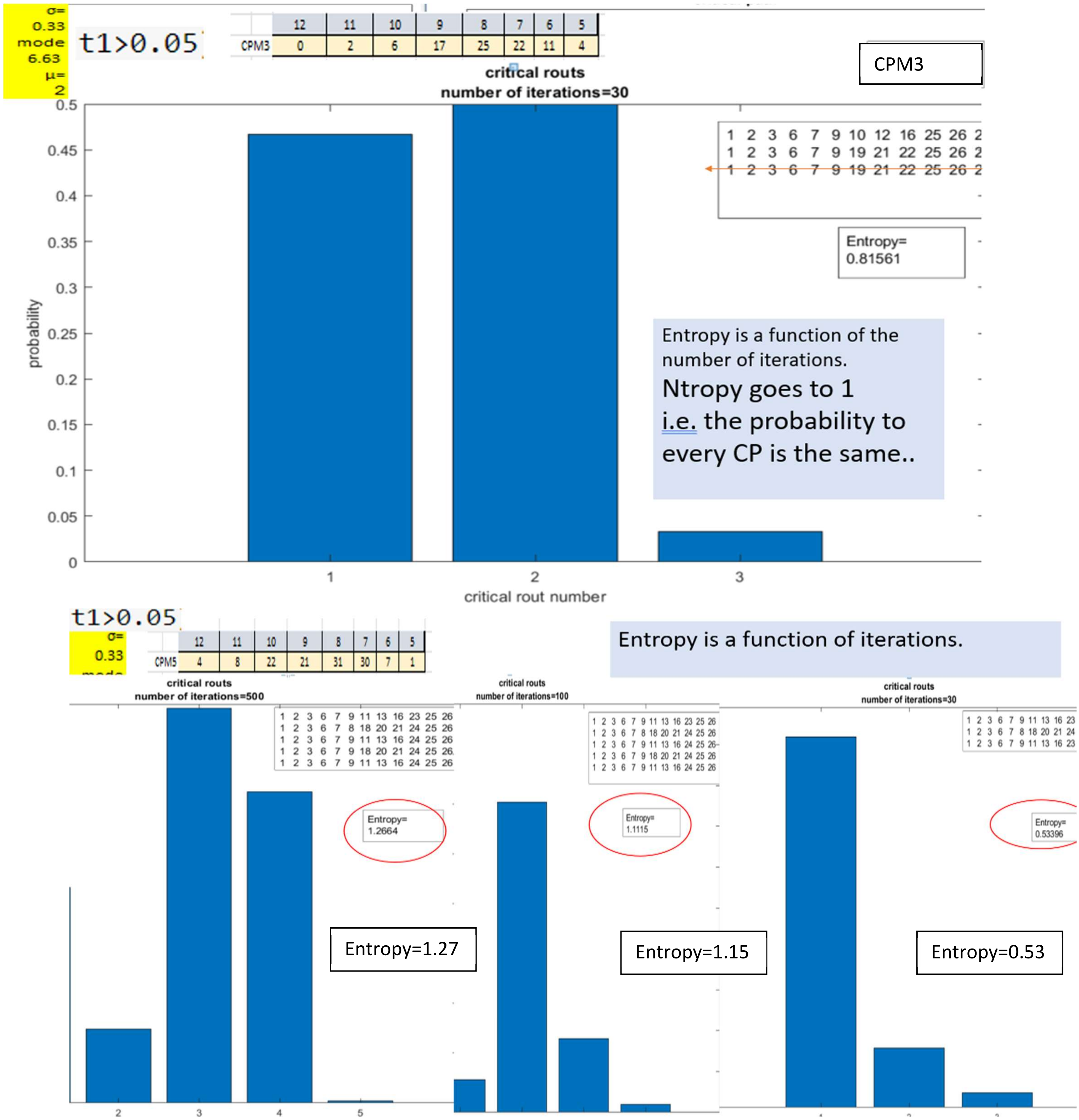


Fig. 14. CPM 3 attractors found after 30 iterations, CPM5 after 30,100,500 iterations

attractors

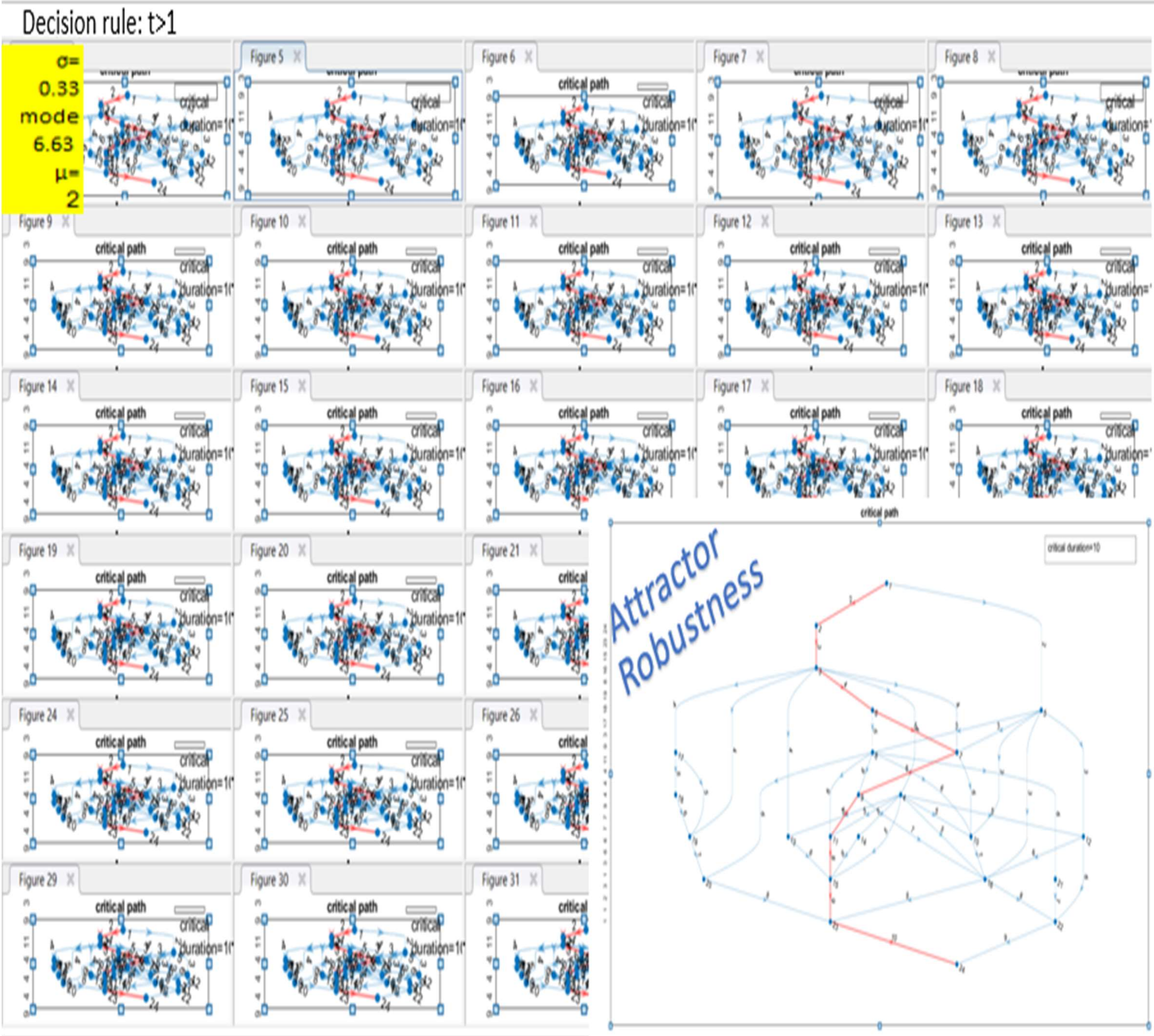


Fig. 15. Robustness of attractor for CPM1

PCA-principal component analysis

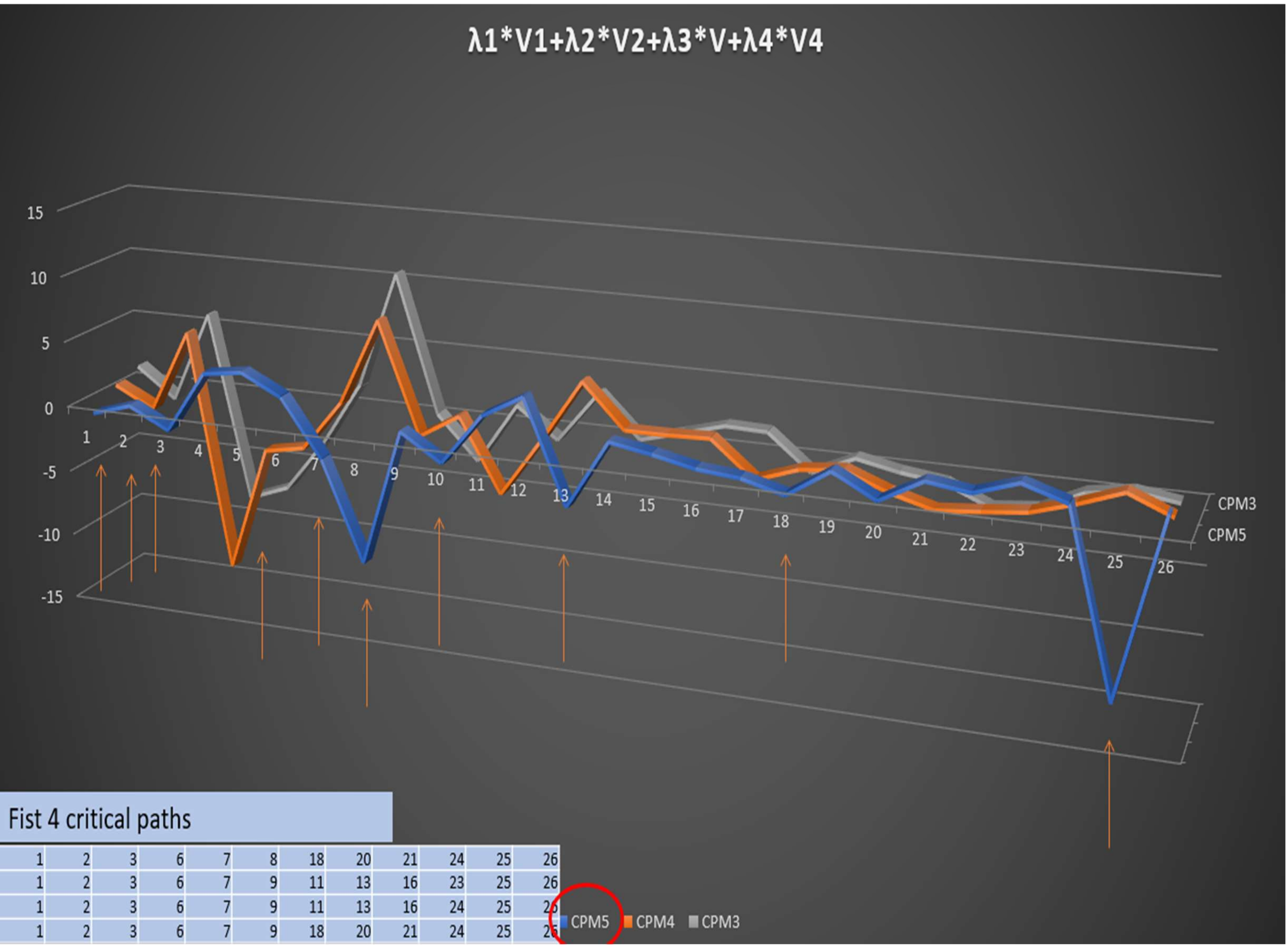


Fig. 16. refraction mode of first 4 eigenvectors

Synchronization

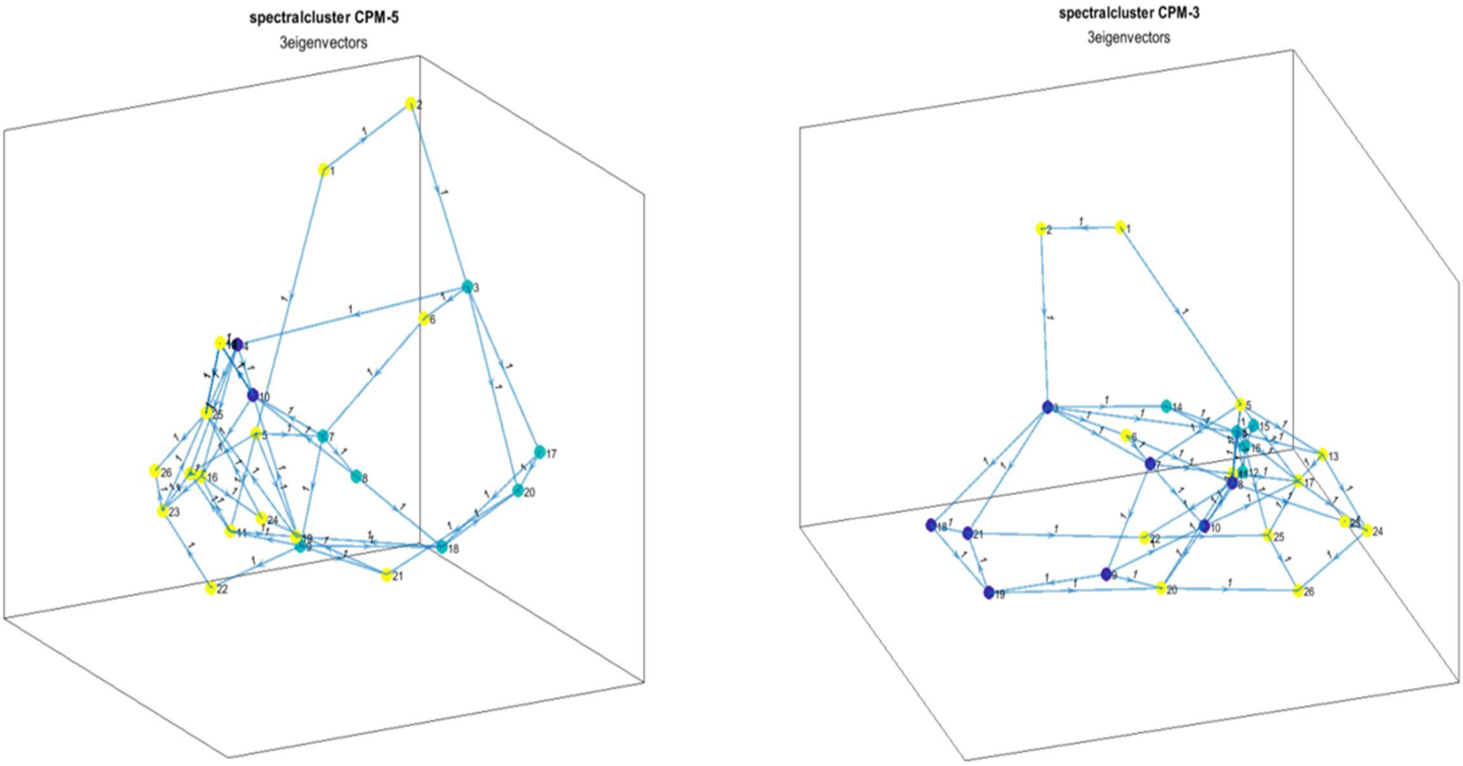


Fig. 17. Three D eigenvector space spectral clustering shows a better synchronization of CPM5

Appendix B- Case-studies

Case-study 1

Imported risk, morphological evolution

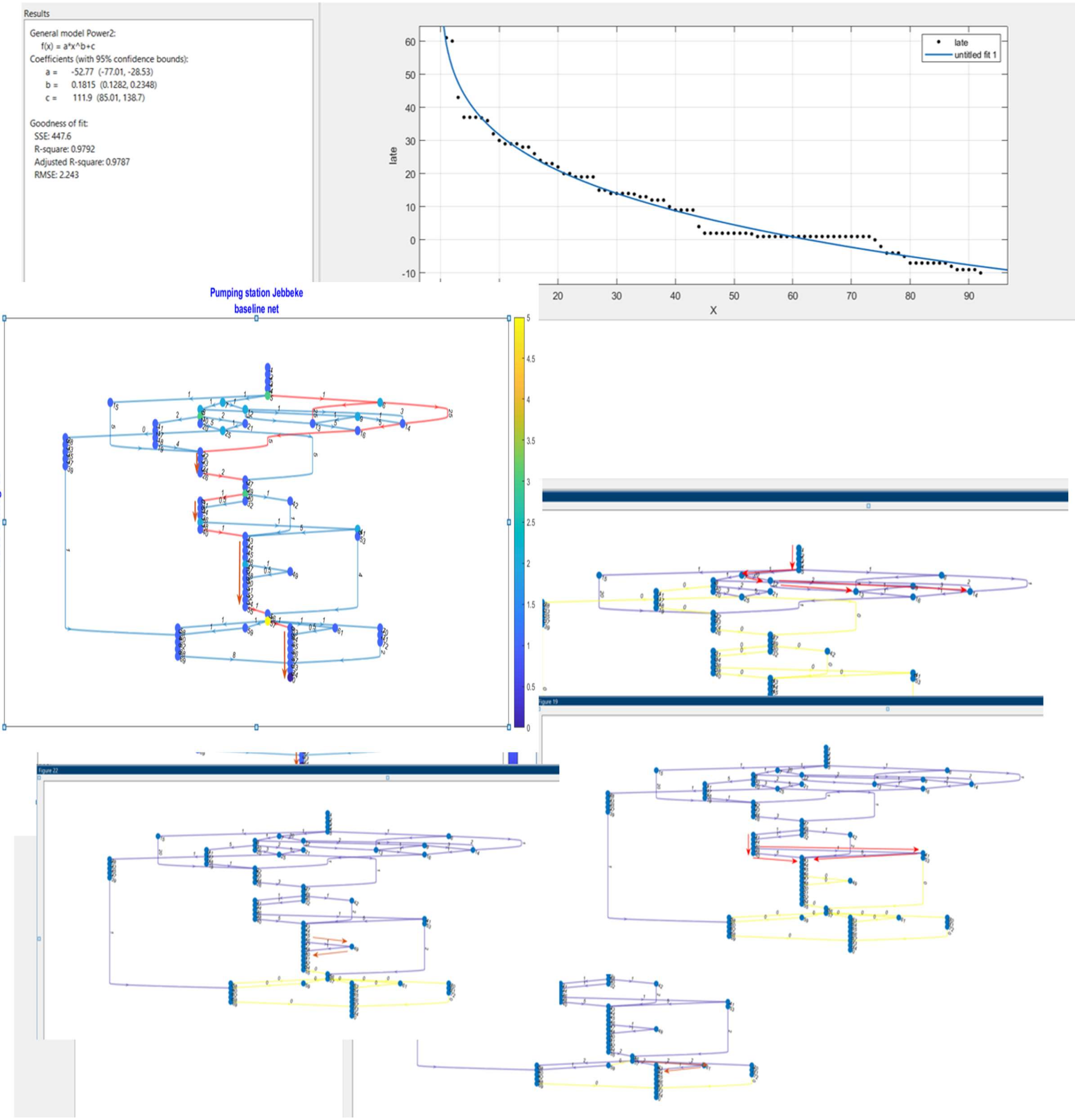


Fig. 18. Pumping Jebbeka power function and CP fluctuations

Fig. 19. Imported risk. Xtickvalues are the time units' numbers.

Case-study 2

Synchronization

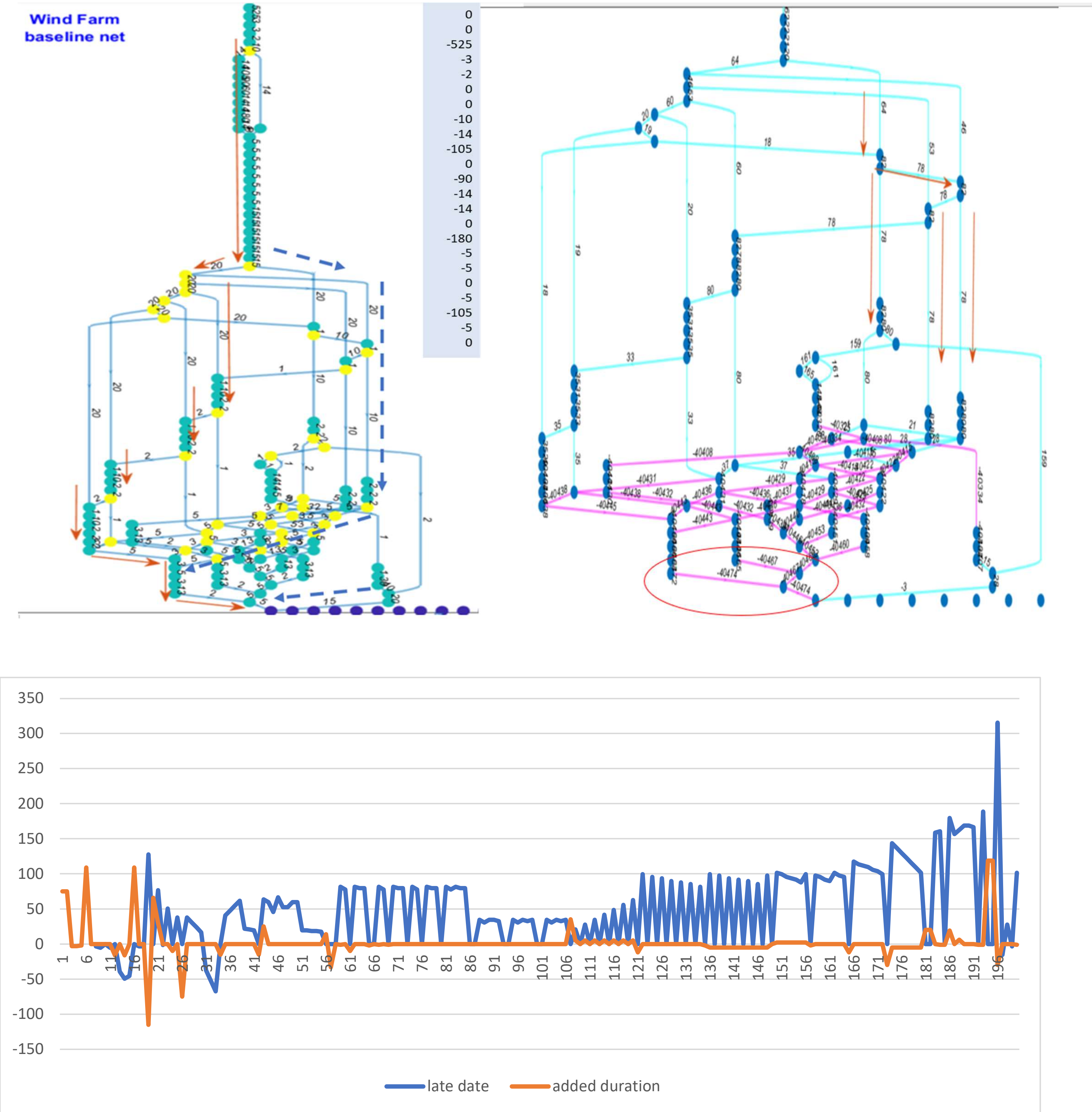


Fig. 20. CP planned [left] vs.. actual [on the right] showing synchronization. The vertical vector are the first few positions in diag(L*H) of Equation 3. Ordinate-time units ordered scale

Case-study 3

Production sequence, in situ production

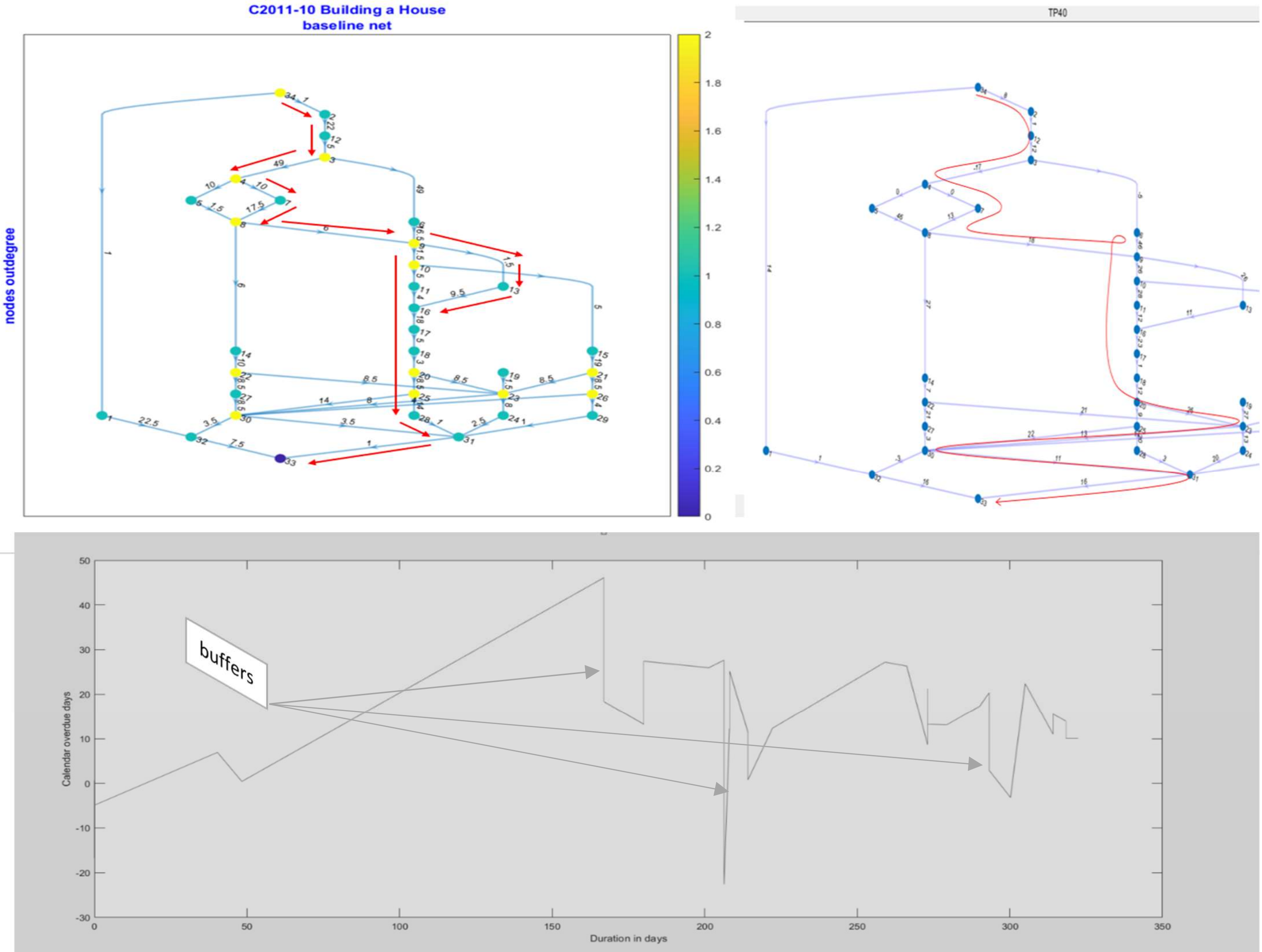


Fig. 21. case-study 3 CP, path directed by buffers

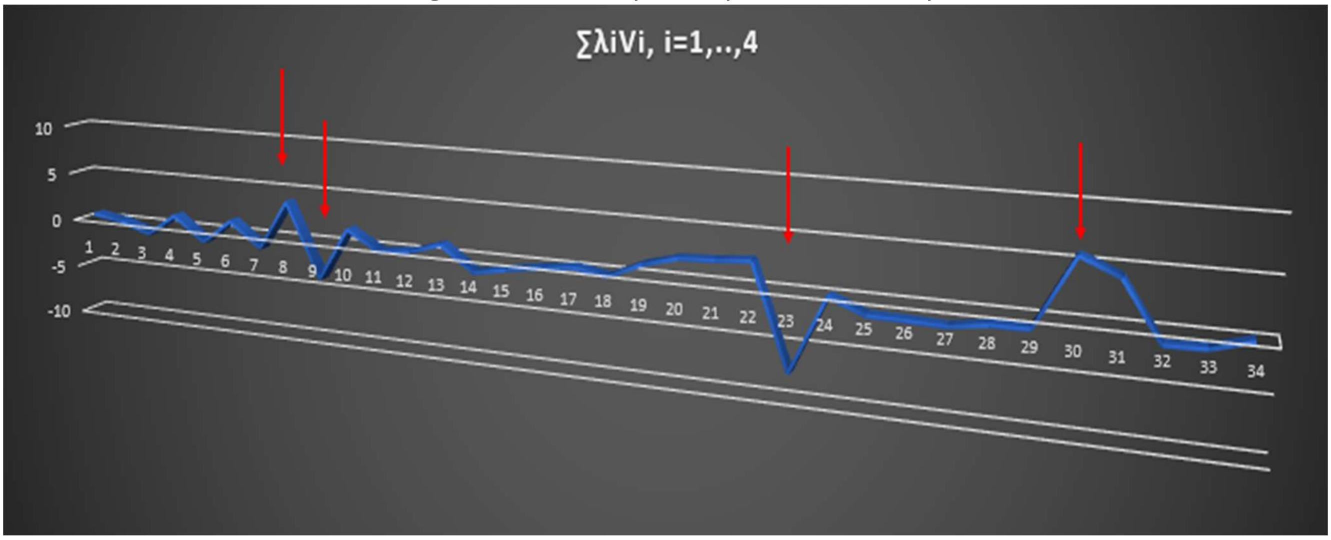


Fig. 22. PCA analysis for case-study 3

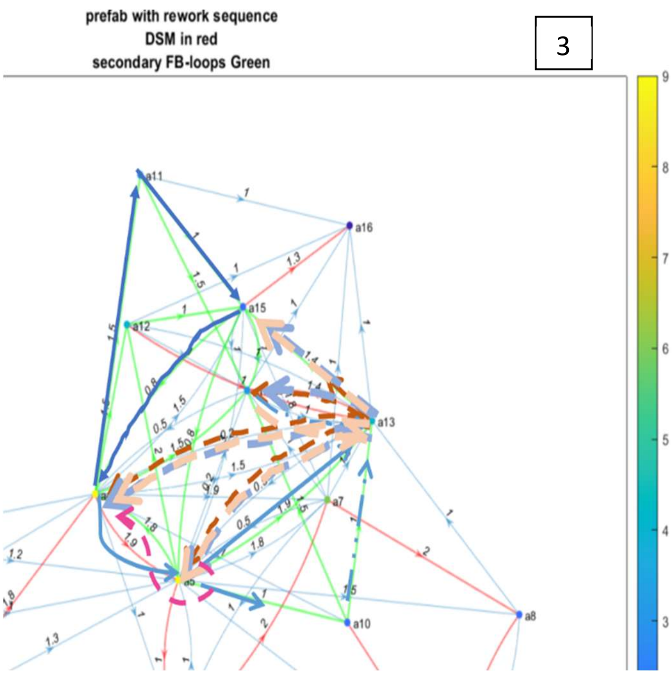
Case-study 4

Coupled activities- rework sequences

Pre-cast project original DSM

	a1	a2	a3	a4	a5	a6	a7	a8	a9	a10	a11	a12	a13	a14	a15	a16		
a1	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	all	Procurement and constraints are not formalized
a2	0		1	1	1											0		[imported risk]
a3	0			1	1											0		
a4	0				1	1	1			1	1	1	1	1	1	0	a4+a5	should be unified to one activity
a5	0			1		1	1	1	1	1		1	1		1	0	a5,10	Wrong
a6	0				1		1									0		
a7	0					1		1					1	1	1	1		
a8	0								1				1			0		
a9	0									1						0	a9,10	Wrong
a10	0												1	1		0		
a11	0													1	1	1		
a12	0												1	1	1	1	a12,a13	should be unified to one activity
a13	0											1		1	1	1	a13,12	not needed
a14	0												1		1	1		
a15	0													1		1	a15,14	Wrong
a16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		

1



3

2

E1^4

	'a1'	'a2'	'a3'	'a4'	'a5'	'a6'	'a7'	'a8'	'a9'	'a10'	'a11'	'a12'	'a13'	'a14'	'a15'	'a16'
'a1'	-	-	-	97.61	121.75	73.77	117.67	97.19	58.75	63.55	30.13	117.31	208.74	208.45	230.97	177.73
'a2'	-	-	-	95.94	114.20	61.80	98.49	86.19	58.29	54.07	21.98	102.52	192.14	195.75	215.93	182.22
'a3'	-	-	-	83.51	94.66	45.92	76.65	61.39	51.14	43.76	18.08	83.90	151.52	148.84	168.81	149.57
'a4'	-	-	-	140.36	153.77	85.61	140.50	109.10	70.08	94.67	37.53	156.05	250.23	247.41	283.24	230.97
'a5'	-	-	-	121.16	159.00	77.48	129.23	87.89	70.24	84.65	44.40	142.47	236.60	241.67	261.09	217.47
'a6'	-	-	-	53.28	52.17	33.01	49.19	47.18	24.89	45.79	11.55	57.53	94.71	86.64	107.04	84.61
'a7'	-	-	-	60.32	75.08	38.58	65.97	48.11	38.14	35.29	17.76	68.26	126.68	135.31	131.76	110.66
'a8'	-	-	-	11.88	15.05	5.78	9.77	5.74	3.28	7.90	4.08	15.89	20.83	23.06	30.55	24.19
'a9'	-	-	-	10.34	10.84	3.71	6.87	2.63	2.11	3.71	2.94	9.44	13.17	17.46	14.94	16.61
'a10'	-	-	-	19.63	22.15	13.16	21.82	14.46	7.56	11.52	7.14	22.80	36.70	34.12	40.54	31.02
'a11'	-	-	-	18.70	22.05	14.00	22.03	17.82	8.40	11.28	5.97	21.58	39.29	38.82	43.31	33.53
'a12'	-	-	-	22.78	30.07	17.32	27.79	20.18	10.25	14.77	9.03	29.03	46.83	49.61	53.95	41.30
'a13'	-	-	-	46.56	51.02	29.29	47.49	37.86	22.31	26.08	11.95	49.88	87.34	86.25	97.31	80.13
'a14'	-	-	-	33.43	45.30	22.88	37.33	27.52	19.17	20.54	11.67	40.37	66.54	71.81	77.10	63.43
'a15'	-	-	-	51.47	54.65	28.47	47.23	38.39	28.94	26.73	10.55	50.88	92.68	88.12	102.09	88.84
'a16'	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Fig. 23. coupled activities cause higher order feedback loops. DSM with errors notes [1], network morphology with some higher order loops trajectories [3], E^4 Boolean matrix [2].

Case-study 5

Coupled activities in infrastructure facility

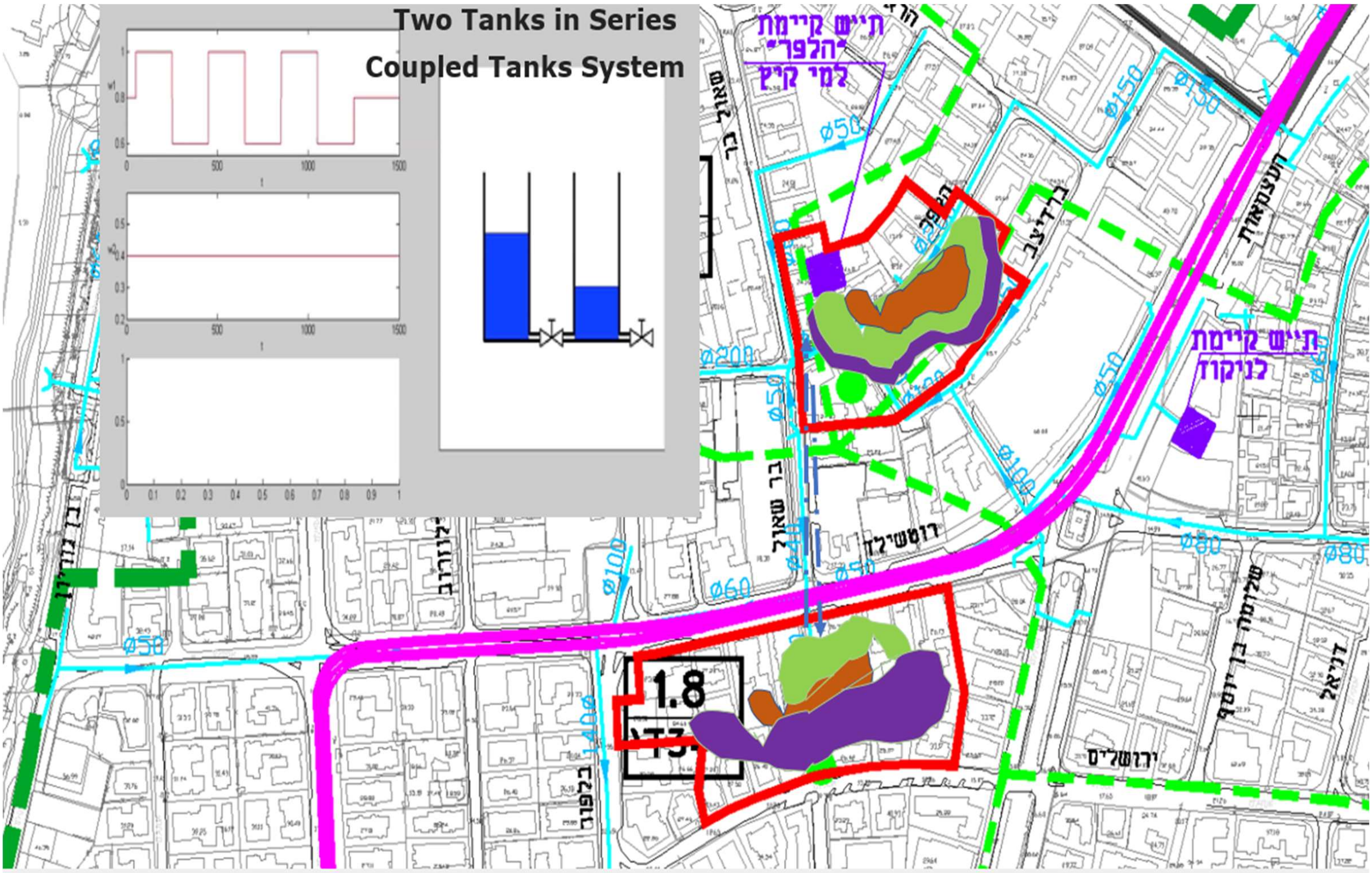


Fig. 24. coupled nodes in infrastructure causing oscillations

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