Theory of Faults (ToF)

Digital Statistic Quality Control in Complex Systems

Niv Yonat[1] | Igal M. Shohet[2,3]

ABSTRACT

Complexity in projects and infrastructure facilities render traditional forecasting and managerial tools ineffective. Complexity manifests in data entropy coupled with materiel flow. Based on faults analysis, an explicatory theory [ToF] is developed mathematically, expanded by numerical experiments, validated by case-studies, and related to practice by participatory paradigm. ToF is applicable for systems characterized by Log-normal PDF. It is shown that power function magnitude distribution is a mathematical outcome of Log-normal PDF. Power function indicates complexity. Complex effects such as avalanche, and emergent traits such as risk behaviours are expounded. Information constraint, information entropy and Digital Signal Processing analysis broadens the understanding of effects of time and morphology, such as bifurcation, multiplication, propagation, and cost and time overruns.
ToF contributes modelling framework and management tools under complexity, it has been used to decipher systems' morphology and behaviour, to direct Quality Control, and to facilitate digital control.

KEYWORDS

Complex Projects and Infrastructures, Construction Defects, Risk Management, Quality Control, Time and Cost Overruns.

INTRODUCTION

Complex projects and infrastructure facilities are protected from aleatoric risk by physical, behavioral, and normative means called barriers. The stochastic manifestation of aleatoric events is described by a plethora of probability distribution functions [PDF]. When barriers are penetrated and aleatoric risk is translated into faults, the log-normal distribution may best describe the statistics of faults (Darren et al., 2005). The log-normal probability distribution is not a rare occurrence, it best fits most construction projects, design, and infrastructure operation and maintenance [O&M]. It is a product of projects WBS [work breakdown structure] and the recursive formations of infrastructure systems and of design (Horvath, 1959). The log-normal PDF is developed mathematically in this work to a power function that represents the magnitude of the faults. The power function is related to complexity. Complexity is manifested in phenomena of Chaos. The butterfly effect for one, stands for small perturbations that cause big effects down-stream, Black-swan events are events that cannot be predicted from experience, there are emergent behaviors, avalanches, and non-linearity that disrupts supply chains and render meticulous software aided time management efforts ineffective. Faults cause morphology changes, entropy inflation, collisions, time changes, and material misallocation, waste, and transportation costs.
There is a gap in the understanding of the origin and inception of faults in construction (Bagdiya & Wadalkar, 2015), (Söderlund, 2004). The epistemic reliance of projects and infrastructures on information suggests a data-driven domain. The literature suggests an information epistemological origin to faults

[1] Department of Civil and Environmental Engineering, Faculty of Engineering Sciences, Ben-Gurion University Israel.

[2] Department of Civil and Construction Engineering, College of Engineering, Chao Yang University of Technology, Taichung, Taiwan, Republic of China

[3] 3 Correspondence I..M..Shohet Ben-Gurion University P.O.B. 653, Beer Sheva 8410501, Israel. E-mail Igals@bgu.ac.il

(Streufert, 1973), (Haksever, 2000), and for cause of faults a bank of literature suggest information overload (Aljassmi et al., 2014). These suggestions do not provide understanding of the mechanisms of creation and propagation of faults, and the literature does not offer effective suggestions for corrective means (Rokooei, 2015). Statistics fails in complex systems because the long tail of the power function draws inference to the low impact occurrences [Fig. 4] and Artificial Neural Network based AI fail because systems generate different outcomes for similar projects [Fig. 18 (2)].
There is also a gap in reliable data, in part associated to liability, risk allocation and prestige and in part to systemic bias (Lopez et al., 2010).
The research objective is to provide a mathematical model to the effects of risk in complex systems, to deliver numerical analysis and predictions of the system response and to provide computational, when possible automated, means of mitigation and corrective actions.
The theory formulation sequence is: the magnitude of the faults of the Log-normal PDF is developed mathematically to show that it has a power function. The power function is analyzed to provide understanding of emergent traits that are common to the construction industry. Entropy is presented. Lists of faults produced by quality control [QC] are digitized to generate a propagating error signal that is fed into the information system. Info-systems have a limit to capacity [called here **IC**], that makes the outcome a threshold phenomena. The systems are modeled as networks. These networks are scale-free. Numerical experiments and simulations elucidate the influencing factors. Time and morphology influence is further examined. Using descriptive statistics and DSP [digital signal processing], a fault database is case studied to support and validate the theoretic findings. Practical knowledge relates the findings to the practice of projects and infrastructure. Prevention and mitigation strategies are discussed and a **PID** [**P**roportional **I**ntegral **D**erivative DSP controller] application is suggested and applied in the case studied.
The graphical abstract [Fig. 1] tracks the trajectory of faults in systems such as projects and facilities.

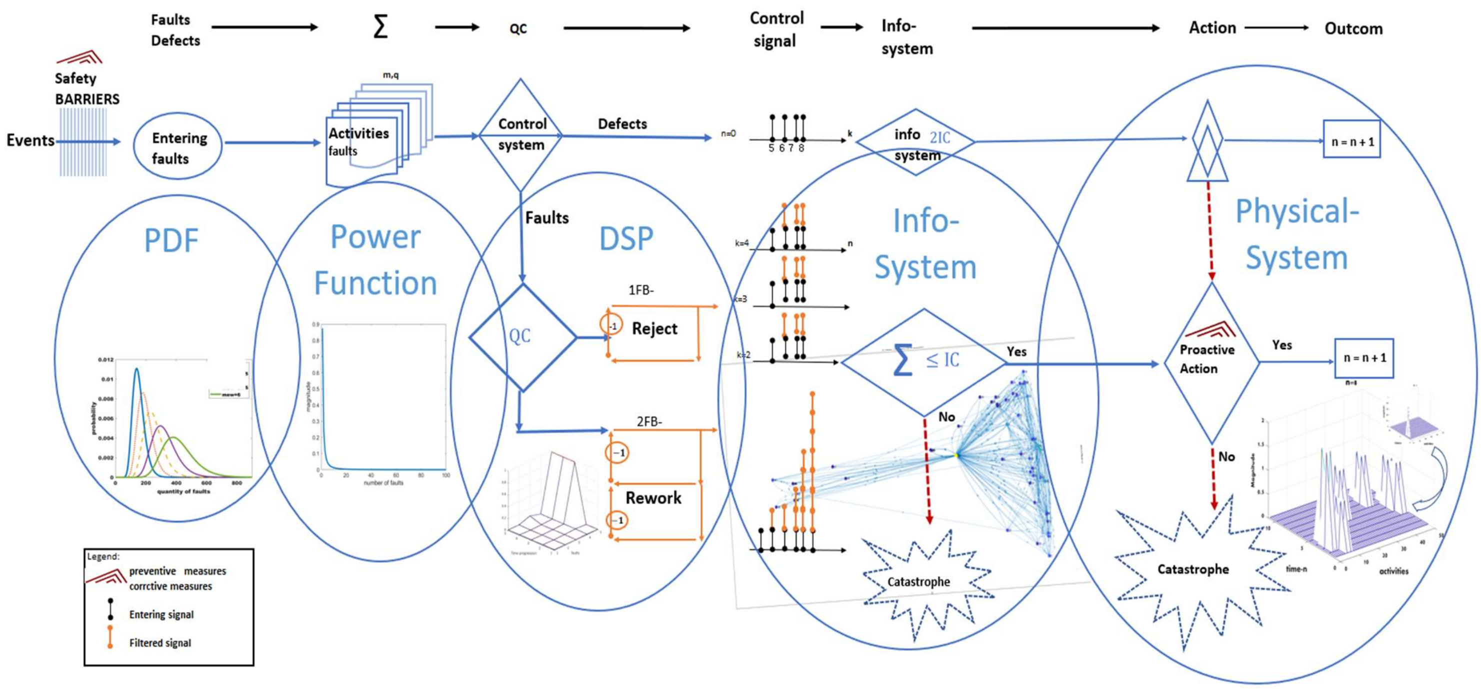


Fig. 1 . Fault progression through a system

The article's framework [Fig. 2] follows the progression of faults [Fig. 1]. The Introduction and Methodology sections are followed by the presentation of the barriers , the PDF, and the development of Power function; DSP layout and the presentation of the info-system are followed by the explanatory factors, time, and the information constraint. Next, preventive and corrective measures are introduced.

QC role is described in relation to DSP and in the database study. Morphological implications, the numerical simulations and experiments results are presented in Appendix A. Applications are presented via a case-study on Appendix B, the discussion integrates the disparate sections and the conclusion summarizes the work.

METHODOLOGY

The theory is developed mathematically, numerical simulations and experiments are used to sustain the presentation, case-study results are used to present analysis tools and applications. "Practical knowing" (Heron & Reason, 1997) maps results to the realities of construction sites and infrastructure projects. Data analysis tools used here are statistics, descriptive statistics, network theory, and DSP tools.

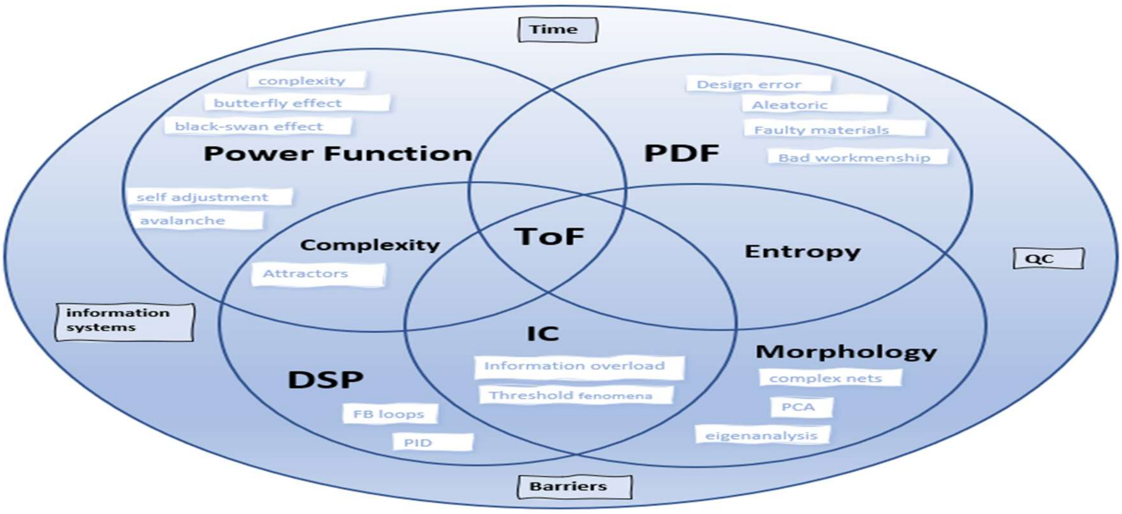


Fig. 2. Fault space

DEVELOPMENT and RESULTS

The cause of faults and catastrophes in the physical world are failures in the information system.
This proposition may be explained in three steps:
Events are blocked from penetrating the systems by barriers (Reason, 1995). Barriers are generated by the code, praxis, drills and by inspection procedures [together the **Via Trita**]. Therefore, barriers are products of information systems. Information system errors enable the penetration of the barriers. Past the barriers, events are met by QC in preparation to be administered to the info-system. At that point, they are denominated **Faults**.
There is an epistemic reliance of the physical systems discussed here on information. Information forms the physical edifices, the barriers, processes, and O&M. It is information that enables the addressing of faults. The info-system is the source of the information and the locus of its processing. Information generated faults originate in the info-system.
The complementary sentence, that the information is the only cause of faults is an outcome of the role of the barriers and QC [Fig. 1] that arrests all possibility of faults not being information faults.

PDF

The Log-normal PDF is presented here by Equations 1-6 and Fig. 3.

$$f_X(x) = \frac{1}{x} * \frac{1}{\sigma * \sqrt{2\pi}} e^{-.5*\left(\frac{ln(x)-\mu}{\sigma}\right)^2} \quad (1$$

$Mean(X) = e^{(\mu+.5*\sigma^2)}$ (2

$StDv(X) = e^{\mu+.5*\sigma^2} * \sqrt{e^{\sigma^2} - 1}$ (3

$Mode(X) = e^{\mu-\sigma^2}$ (4

$x = e^{\mu+z*\sigma} \quad x \in X$ (5

where z=$ln(x)$ is normally distributed N(μ, σ). (6

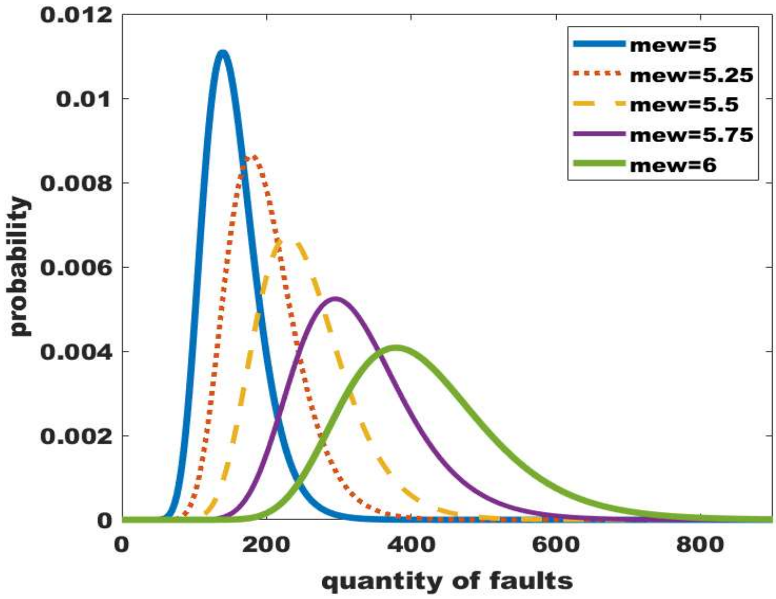


Fig. 3. PDF(X) for σ =0.25, different μ

It is evident from Fig. 3 that the quantity of faults reported in the literature (Flyvbjerg et al., 2003) [be it mean or mode of the sample] may be generated by different combinations of μ, σ. On Fig. 15, a Log-normal PDF (μ=4.9, σ=1.7) was generated for the entire database of Appendix B.
μ and σ are functions of time [Fig. 16 shows that stdv decreases in time +Fig. 17 shows mean to increase with time, from equations 2,3 it is evident that this is possible only if both μ, σ are f(t)].

Power function

The quantity of faults of the Log-Normal variable is exponentially related to z [Eq. 5]:
$x = e^{\mu+z*\sigma} = e^{\mu} * e^{z*\sigma} \sim e^{z*\sigma}$,
z has a normal distribution N (μ, σ):

$$P_z(z) = \frac{1}{2\pi} e^{-\frac{1}{2}z^2} \sim e^{-\frac{1}{2}z^2} \quad (7$$

thus:

$$P(X) = P(z)\frac{dz}{dx} \sim \frac{e^{-\frac{1}{2}z^2}}{e^{\sigma z}} = x^{-1-\frac{z}{2\sigma}} \ , \forall x \in X \quad (8$$

$$b = 1 + \frac{z}{2\sigma} \quad (9$$

$$P(X) = ax^{-b} \qquad , \forall x \in X \quad (10$$

Therefore, the probability distribution [Equation 10] of the magnitude of faults is a power function.

(Newman, 2005) reports the work of (Miller, 1957), where for the frequency of words is divided between letters:

$$P(x) = \frac{1-q}{m} \qquad x \in X \qquad (11$$

$$b = \frac{2\,ln(m) - ln(1-q)}{ln(m) - ln(1-q)} \qquad (12$$

We found that calculating for "q" as a post-factum project mean, yield some good predictions for construction projects, where "m" represents number of activities. Fig. 4 is generated for project duration of N=192 weeks (3.5 years) that generates $\sum x$ =100 faults in 50 activities. The probability of having a fault in a time period is $\frac{\sum x}{N} = 1 - q = 0.52$.
"b" was calculated from Equation 12. The scaling parameter "a" was calculated by integrating Equation 10:

Fun1

```
fun= @(x,b) x.^-b;
y=integral (@(x) fun(x,b),1,m);
a=1/y;
```

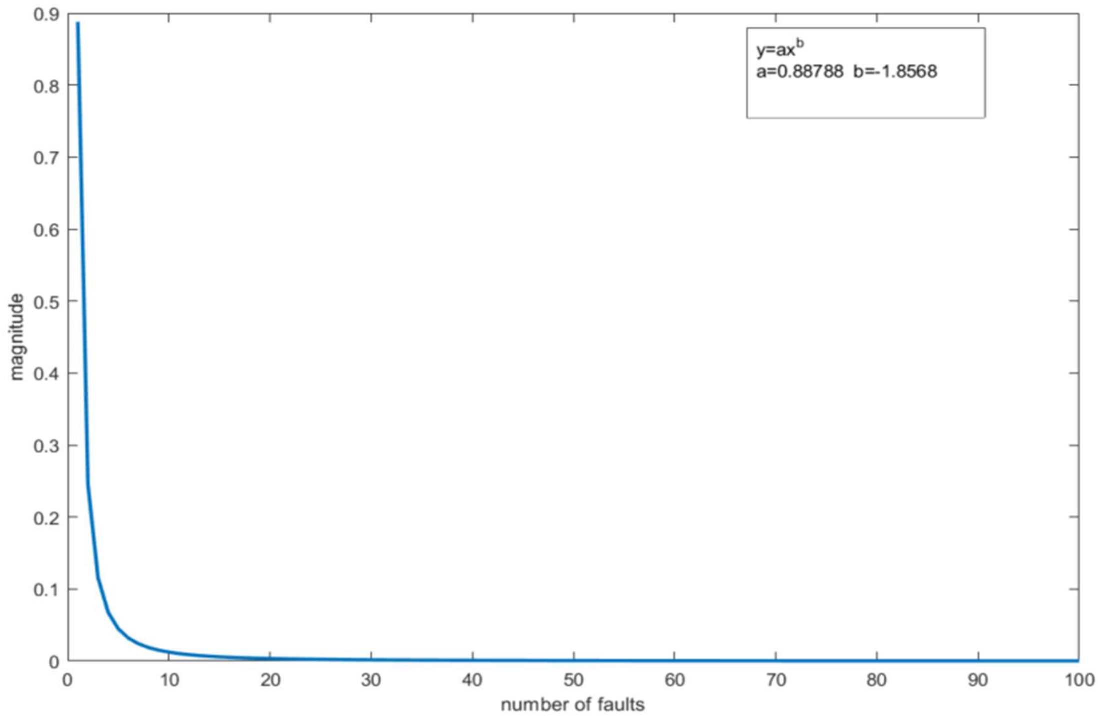


Fig. 4. Power function generated using Equations (10), (12), Fun (1) for m=50, $\frac{X}{N}$=0.52, a=0.89, b=1.86

Fig. 18 (3) and Fig. 19 (3) were generated using the same procedure.
As x_{min} goes to zero, the magnitude of faults goes to infinity.
There is an implicit assumption that X may be dealt with as a continuous variable.
X < 1 implies faults that may occur every few projects. "a" is a scaling parameter. When "a" scales to 1, a>1 implies that the cost of a single fault may be greater than the cost of the entire project. In [Fun1] a=a(X_{min}). When X_{min} is not bound toward zero, y is not bound.

It is useful to present the function on log-log scale [Fig. 5, Fig. 19 (3)].

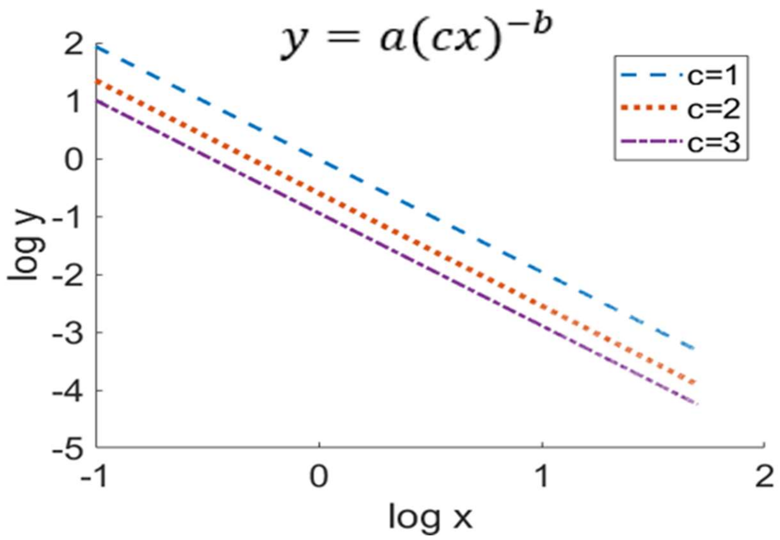


Fig. 5. Log-Log Graph of power function

Power function is scale-free. This usually refers to the identity of the function for all scales of event, for instance, avalanches are occurring in any scale, the production of fractals- repetitive sub-formations.
Fig. 5 presents the function for scaled " x ". Where "y" stands for risk, "c" may represent different risk scales: cost, time, probability. Multiplying the variable only changes the ordinate.
Fig. 6 presents the power function for a scaled power parameter "b".
"c" may represent a move from high quality (lower "b") to lower quality (higher "b").
This move may represent the same project at different time [b=b(t), case-study Fig. 18], or different segments of the industry [b=b(m, q), Equation 12].

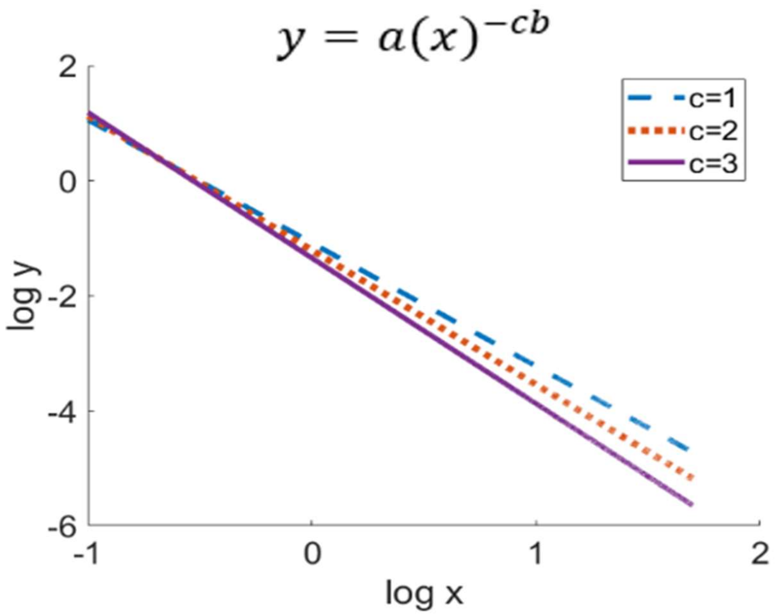


Fig. 6. Log-Log Graph of scaled power values, b=1.946

The relation between “b” and “q” generated by Equation 12 [Fig. 7]:

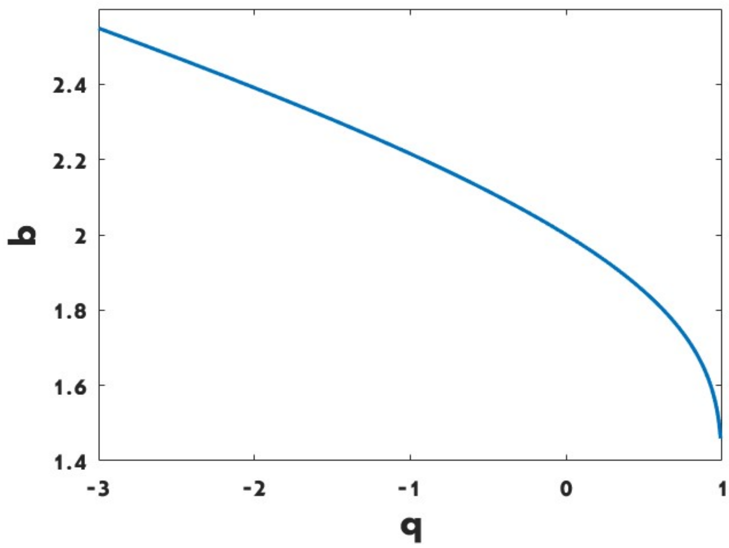


Fig. 7. Power shift as a function of “q”

A project of N=150 weeks and a total of 300 to 600 faults, yields $q \geq -3$ b<3. For q<0, there is a certainty (1-q>1) of faults on every $n \in N$.
Projects with b>2 accumulate a longer tail of small effect faults, and a major event of low probability. 0<b<1 was machine fitted to large infrastructure error logs (case-study Fig. 18). 1.3<b<2 relates to well managed projects and b>2 to more chaotic projects such as residential buildings.
According to (Newman & Sneppen, 1996), b>2 implies two attractors. Here two IC, In the construction industry there is one IC for faults and another IC for Defects [defined on next chapter].
A move from high fault probability projects to lower probability projects is a move to the right on the "b" curve of Fig. 7, and a move between the curves of Fig. 6. This represents a move from a renovation project to residential construction to infrastructure and to high impact projects, such as a nuclear reactor (Mills et al., 2009). [q=q(m), table 2 where total probability is the sum of all “m” probabilities; q=q(morphology), Fig. 10 v.s. Fig. 13 where morphology magnifies “q” by rank; q=q(t), Fig. 9].

Entropy

Say we have a Fig. 4 type probability distribution with a very large number of small magnitude faults and a very small number of high magnitude faults. For a total number of faults “n”, the entropy goes to a limit:

$$H(x) = \lim_{n\to\infty}\{-\textstyle\sum_k^n p(x)\, log\,(p(x))\} \cong -\sum \frac{1}{n}\, log\frac{1}{n} = \frac{n}{n}\, log(n) = \, log\,(n) \qquad (13$$

This is the maximum possible entropy for n. “n” itself is not bounded, rather, it is inflated by the entropy A move to the right on Fig. 7 entails information gain.
The space G(N,E,T) is a graph where the nodes [N] are activities or locations, and the edges [E] are the information links. The state variable “a_i” is the number of faults in edge ”E_i”. Faults are imported and/or produced by the nodes and edges.

$$\frac{dG}{dt} = \frac{\partial G}{\partial N}\frac{\partial N}{\partial t} + \frac{\partial G}{\partial E}\frac{\partial E}{\partial t} \quad , \qquad \frac{\partial N}{\partial t} \geq 0, \frac{\partial E}{\partial t} \geq 0\, , \frac{\partial G}{\partial N} \geq 0\ , \frac{\partial G}{\partial E} \geq 0 \qquad (14$$

Locations are constant producers of information, locations may be added and links are generated never to be deleted.
Entropy is introduced to the system externally [e] or produced internally [i]

$$\frac{dH}{dt} = \frac{d^eH}{dt} + \frac{d^iH}{dt} \qquad (15$$

In constant production situations, $\frac{dH}{dt} = 0$ and entropy production is at its minimum, [entropy is not limited, therefore, there is no max to the function]. $\frac{dH}{dt} = 0$ because design changes are not allowed $\frac{d^eH}{dt} = 0$ and all internal faults are corrected in each discrete unit time $\frac{d^iH}{dt} = 0\ ,\ t \in\ 1,2,3, \dots$.
Entropy is a measure to the amount of information needed to define the state of the system, $\frac{\mathrm{dH}}{\mathrm{dt}}$ is a measure of the normalized change in "internal energy" of the system.

DSP

On the construction site, for each unit of time $n \in N$, a work-order is issued to workers, suppliers, and subcontractors, specifying work, means and materials. Each specific assemblage constitutes an "activity". When the execution of an activity is completed, a signal that delivers the information- "DONE" is produced.
QC may approve = "Ok",
or "Reject" = to be rectified prior to approval,
or not-approve = "Rework".
The QC rulings are DSP control operators [portrayed on Table 1]:
> pass ["Ok"],
>> back a step= one **F**eed-**B**ack loop [1FB] ["Reject"],
>>> back two steps= double **F**eed-**B**ack loop [2FB] ["Rework"].
Past the filters, the signal advances into the info-system for processing.
A "Fault" is what causes a Reject or a Rework in the info-system.
A "Defect" is a small fault that is small enough not to cause an info-system response.
Together they are referred to as faults.
Change orders cause rework in the info-system, therefore change orders are faults.
A unit signal is represented here by the Kronecker delta δ[n] =1. The time n, $n \in N$ a discrete time set.
A δ[n] signal entering one 1FB-loop produces a constant outcome of 1,1,1, 1,… as long as it is not terminated. The signal is augmented to the system's current data load.
The 2FB loop is an amplification sequence generated by the accumulation of previous gain. A δ[n] signal directed to a 2FB-loop causes a Fibonacci scaled signal- 1,1,2,3,5,8,13… (Freeman, 2011).
The DSP operators that produce the feed-back loops are called "**Filters**." The filters are Linear Time Invariant [LTI]. The control δ[n] signals are LTI. Signals only accumulate, scale and time-shift. The power function [presented in the previous section] determines the magnitude of the faults. The control signal is scaled by the power function. The PDF determines the recurrence of the signal. The signal passes through the filters, and into the information system, where the Information Constraint determines the eventual outcome. [Appendix A-numeric experiment A.3]
The response of LTI systems are functions called "Impulse Response," annotated h[n]. Systems are injectively determined by it. The outcome y[n] of a specific fault signal vector $x[n]$ is the convolution (denoted by "∗") of the impulse response h[n], and the fault vector signal $x[n]$: For an LTI

$$y[n] = x[n] * h[n] = \sum_{k=0}^{K-1} h[k]\, x[n-k] \qquad (16)$$

This entails breaking down the vector to its respective spectrum (=K phases), a procedure made simple by choosing a δ[n] signal. Time domain:

$x[n] = \sum_{k \in z} \delta[n-k]$ (17)

The Frequency domain is the Fourier transform of the time domain, or Z transform for discrete signals. The low case variables stand for the time domain x(t), y(t), h[n], etc. the upper-case X(s), Y(s), H[z] stands for the transform:

$\mathbf{X}(\omega) = \frac{2\pi}{N} \sum_{k \in z} \delta[\omega - \frac{2\pi}{N} k]$ (18)

A specific phase ($\frac{2\pi}{N} k$) matches a specific activity (k).

The Z transform of x(n) is:

$\mathbf{X}[z] = \sum_{n=-\infty}^{+\infty} x[n]\mathbf{z}^{-n}$ (19)

For an eigenvector signal $x[n] = \mathbf{z}^n$,

$y[n] = \sum_{k=-\infty}^{+\infty} h[k]\, x[n-k] = \mathbf{z}^n \sum_{k=-\infty}^{+\infty} h[k]\, \mathbf{z}^{-k}$ (20)

$H[\mathbf{z}] \equiv \sum_{k=-\infty}^{+\infty} \mathrm{h[k]}\mathbf{z}^{-\mathrm{k}}$ (21)

$y[n] = H[\mathbf{z}] * \mathbf{z}^n = \lambda\, \mathbf{z}^n$ (22)

H[**z**] is the eigenvalue of $\mathbf{z}^n$.

H[**z**] is called the Frequency Response.

Any signal can be synthesized from eigenvectors

$x[n] = \sum_{k=-\infty}^{+\infty} \mathbf{X}[k]\mathbf{z}^n$ (23)

$y[n] = \sum_{k=-\infty}^{+\infty} H_k[\mathbf{z}]\, \mathbf{X}[k]\, \mathbf{z}^n$ (24)

$\mathbf{z}^n$ is eigenvector of all LTI. **Z** may be any complex number in the region of convergence [ROC].

$for\ n = k, \quad \mathbf{z}^{n-k} = \delta[n-k]\ \therefore$ (25)

Therefore $\delta[n-K]$ are eigenvectors of all LTI.

The difference equation for the 1FB-loop is:

$y[n] - y[n-1] = x$ (26)

Z transform on (24) yields:

$(1 - \mathbf{z}^{-1}) * Y(\mathbf{z}) = X(\mathbf{z})$ (27)

$H[\mathbf{z}] = \frac{Y[\mathbf{z}]}{\mathbf{X}[\mathbf{z}]} = \frac{1}{1-\mathbf{z}^{-1}}$ (28)

Table 1 summarizes the DSP tools used here.

The operators	**The difference equations** (Freeman, 2011)
Pass	y[n]= x[n]
Reject feedback loop	y[n]= x[n]+αy[n-1] (24.2)
Rework double feedback loop	y[n]=x[n]+αy[n-1]+βy[n-2] (29)
Reject transfer function	$H(\mathrm{z}) = \frac{1}{1-\mathbf{z}^{-1}}$ (26)
Rework transfer function	$H(z) = \frac{1}{1-\mathbf{z}^{-1}-\mathbf{z}^{-2}}$ (30)

TABLE 1. The DSP control operators.

A delay in signal causes a delay in the system response:

$\delta[n-\tau] * h[n] = h[n-\tau]$ (31)

The phase shift is

$\varphi = arg\ \mathrm{H(s)}$ (32)

The signal, a linear combinate of the "k" activities, has one frequency [Equation 18]. The outgoing signal has the same frequency, unaltered by the LTI system [Equation 22].

If the incoming signal has a different period than the site's signal, or if subcontractors or supply chains work on different periods, there are delays when a new period evolves to the lowest common denominator. When difference in periods causes the system to be out of sync, stuttering halts in work sequence occur, accompanied by constrained resources and collisions (Hosny et al., 2020).

Time

Time affects the system through various venues:

1. Duration: the duration of activities, time is an entropic cause for errors causing fatigue, carelessness, pressure, outdated design, and inadequate code assimilation, rendering the barriers ineffective (Love et al., 2012).
2. Repetition: A repetitive process with a non-diminishing fault additive and no correction bifurcates rapidly. [Appendix A.1]
3. Morphology: time generates trajectories of multiplication and propagation of faults on the spatio-temporal map [Fig. 20].
4. Morphology change-info-system: time changes the morphology of the info system [Fig. 14].
5. Morphology change-physical system: time changes the morphology of the system [m=m(t)].
6. Phase shift: Time shift causes a phase shift, and vice versa (Trigo, 2019):
   $$DTFT\ \{\textstyle\sum_{k\in Z}\delta[n-kN]\} = \omega_0 \textstyle\sum_{k\in Z}\delta(\omega-\omega_0 k) \qquad (33)$$
   Phase represents activity, therefore, the project is out of the designated activity, this causes time delays and cost inflation.
7. "Crashing time": A "corrective" action of recuperating lost time by scaling down the duration of activities adds to the previous outcome:
   7.1. Information loss.
   7.2. A time delay of an incoming fault is scaled up by the scaling factor:
   For $y[n] = x[\alpha n], \alpha > 1$, a delay in time of τ:
   $$y[n-\tau] = x[\alpha n - \alpha\tau] \qquad (34)$$

The Information Constraint [IC]

Definition: The Information Constraint is the limit on the capacity of an info-system to process the load caused by the Σ("Reject" + "Rework"). The capacity is restricted [Fig. 17 (2)- the IC threshold]. There is little redundancy in the info-system because projects are organized for efficiency, and resource allocation is optimized to minimum cost (Streufert, 1973). The Information Constraint is the system's attractor (Newman & Sneppen, 1996), and systems self-organize to be stable at it [Self Organized Criticality- SOC (Kadanoff et al., 1989)]. The IC self-adjusts to be "correct" (Heyligen, 2002). Past the IC threshold the system avalanches. On Fig. 17, project 22 avalanches after 5 FB iterations, thus the outcome corresponds with table 2].

Factors that aggravate the actual information load on the info-systems are:

1. Allocation changes: The convolution of fault vectors in the info-system causes stacking [Fig. 8]. Pressing issues such as created by the construction and authorization processes require immediate attention and resources reallocation, eventually idle resources and cause inefficiency, latency and resentment. Multitasking aggravates the effects.
2. Morphology: Info systems are complex nets [] characterized by preferential attachment that is manifested by rank. Information load is related to rank not only proportionally, but also by liability and prestige. High rank individuals not only carry a burden scaled by rank but also have to deal with contractual, litigation, insurance prestige implications. Scale free nets morphology propagate data ever faster and cause one agents problems to become all agents problems.

3. Morphological changes: The info system nets' morphology is modified by time and faults [Fig. 14], most notably generating higher order loops causing more rework and causing vexation and apathy, upsetting the effects of buffers and planning. Moreover, the effects of liability and prestige sever triadic connections and form bridges of delayed and biased connectivity [Fig. 14].

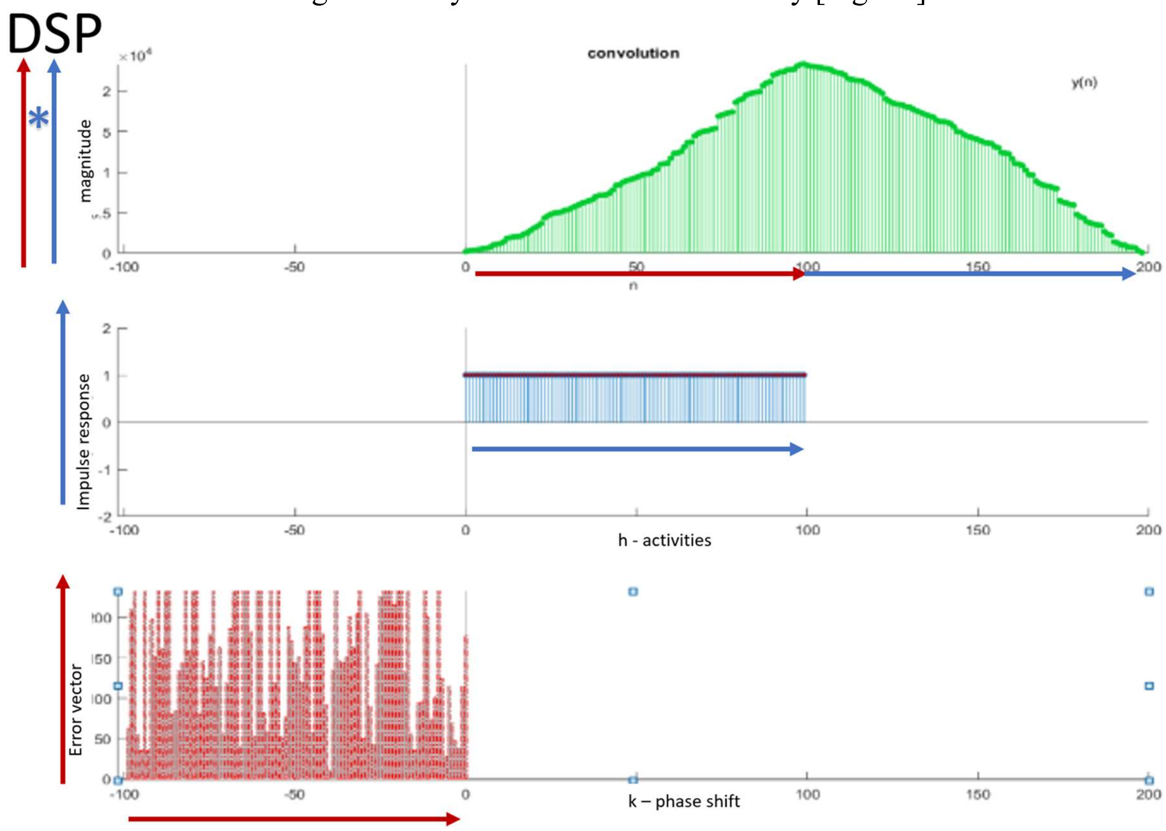


Fig. 8. Information convolution in info-system. In red the entering Redo orders [Equation 19], in blue the system Response [Equation 20], in green the convolution [Equation 16].

Preventive Means

The preventive means are the sum effects of the barriers: Physical and normative protections such as dams and their O&M, QC in its capacity of blocking bad materials by test labs, bad practices by enforcement of praxis and bad design by BCBs [=building control bodies], and the info-system in its complementary role as counterparty to all the above and as supplier of current protections, practices and code, drilling the system, proofing the design, etc. For prevention, ToF practices supply means to locate where the barriers are penetrated, and suggestion of better directed corrections and drills.

Corrective Means

Faults are related to epistemic authority (agents), and defects are related to epistemic rationality (means, norms), ((Broncano & Vega.E, 2019). Therefore, different causes govern faults and defects. Usually there is time to stop a pernicious event before it avalanches because the fault propagates in a physical network while the corrective means are developed and applied on the information network. Systems such as power grids may present examples to the contrary.
Corrective means for faults are behavioral: An energetic, rapid response with open mindedness (Hare, 2009) and a trouble-shooting culture (Müller & Jugdev, 2012), (Pinto & Slevin, 1987). In many instances these are not applied.

To address this gap we suggest a system of data analysis based on DSP, descriptive statistics and PID management that produces real-time alerts and initiates remedial actions [Appendix B].
For infrastructure systems there is a possibility of fully automated response, based on the above tools and DSP controllers. An automated system using DSP controllers was developed for a municipal storm-water system.
For defects correction we suggest the application of the second IC system to create 1FB and 2FB loops. This would enable the application of the above means.

DISCUSSION

The Via Trita constitutes the barriers that shield projects and infrastructure from aleatoric risk. In case of divergence from the Via Trita, small perturbations may cause consequence of unlimited magnitude [Fig. 9]. That is a cause of the conservativeness of the construction business.
The aleatoric risks may manifest by a variety of PDF, but the system response is always Log-Normal. This is an outcome of repetitive sub-formations [WBS] (Horvath, 1959). Log-Normal PDF was machine fitted here [Fig. 15] for the entire case-study database presenting a high STDV. High STDV is recurring in our findings, caused, most notably, by degraded morphological structures, threshold phenomena, emergent behaviors and sociological bias. All causes noted above are presented here, save for the first that was presented on (Yonat et al., 2022). In (Yonat & Shohet, 2022) we showed that the smallest perturbation in morphology yields the emergence of varied responses, modifying critical paths, criticality indices, entropy and Laplacian stdv. The last finding demonstrates that the system itself is altered. Seemingly identical systems are disparate, the same system modeled with the slightest variation yields a different outcome.
Power functions represent the magnitude of faults. Power functions are a mathematical outcome of the Log-Normal PDF [page 4]. White noise [Fig. 19 (4)] consistently emerge in the data, indicating that the actual functions are of the form: $y=a*x^{-b}+c$. Power functions are demonstrated multidimensionally, manifested spatially and temporally and on axes of traits [Fig. 5]. Faults power functions indicate complex behaviour [Fig. 19]; power function node degree rank distribution [Fig. 14(1)] indicate scale-free network morphology. The emergence of repetitive sub-formations [Fig. 19 (4)] is cause and outcome of complexity. The scale-free trait is the reason why uneven, biased, and partial datasets [Appendix B], still produce reliable results. The power factor magnitude facilitates segmentation of the market [Fig. 6, Fig. 7], the stupendous number of small effect faults [Fig. 18 (1)], and the high magnitude faults of low probability [log x<0, Fig. 18 (3)]. X_{min} is not bound toward zero, therefore the magnitude of the faults [“y] is not bound. But the power function is not symmetrical, the distance to the abscise diminishes more rapidly than the distance to the ordinate. The function has different effects in the different domains, for $2<b<3$ finite sub-graphs are formed (Albert & Barabasi, 2001) and in the presence of randomness, the spatial overlap between subsequent avalanches becomes insignificant, and ultimately a critical state is not reached. “b” is an order parameter. These observations constitute a negative correlation between quality and risk, sustained by Fig. Fig. 7. The negative correlation between quality and risk enables the general neglect of quality. This comes with a “price” of higher entropy and information loss. Entropy gain is reversible to some degree, but at a high cost. Entropy gives a mathematical meaning to the epistemic reliance of the physical systems on information .The Graph of physical locations and their information edges has a nonnegative time derivative [Equation 14], meaning that locations may be added such as in the construction process and nodes are added such as in the operation & maintenance period, but once established, they cannot be undone. Construction site systems preference is to adjust to poor quality. Systems develop robustness, manifested in high tolerance to defects based on power function generated diminishing effect of faults [Fig. 18 (3)], defect insurance (Ilozor et al., 2004), compensation and litigation procedures, a "start-fail-flee" strategy that is sub-contractors’ recourse to incidents of high magnitude failures (Abdul-Aziz,

2002). “b” is a function of time not only because b=b(q,m), q=q(t), m=m(t) [Equation 12]. “b” is affected also by morphology, therefore by time generated morphological changes in the systems. Time is a factor in all influencing factors, acting as an accelerator. Time and morphology are interchangeable [Equation 33]. Fig. 5 shows that time and money effects are interchangeable. Equation 34 has a sound intuitive meaning: on account of a time crash when the discrete time unit is crashed by α, an out of site event affect is scaled by α, this is a measure of the production gain in that time span. But there is a more general implication, a Debora number of De≡site process time divided by design process time<<1. This implies an innate α of this magnitude. This α generates the catastrophic effects of design changes [mutual information is scaled by α].
Complexity manifested in phenomena such as black-swan and the butterfly effects sets limits to prediction owing to non-linearity. Yet, there is a possibility for some measure of prediction. One approach is to trace the trajectory of propagation. In Fig. 20, a 3D cause-spatio-temporal trajectory of faults is traced, projecting the progression of faults to avalanche. In this specific example the cause back-traced was a contractual breach which indicates barrier penetration and therefore the corrective action was directed to correction of the preventive means. Another approach is the use of digital tools. On Fig. 17 an integral of open faults was applied. A correlated avalanche immediately sallies. The avalanche commenced at the systems part of the project [brown] and crushes through the engineering [blue] part and eventually to the control system [red graph]. The origin of this disaster was an erroneous subletting of the systems to DB entities, such that coordination was hampered. Here the ominous change in gradient [=the derivative of Fig. 17] should have been a stop sign, and immediate corrective measures should have been applied to design long before the avalanche became evident on the integral. Regrettably, corrective means were not implemented, and this mega-project was not saved. The application of data-analysis tools enables real-time prevention and/or mitigation and in post-factum analysis, - for claims.
Practical knowing dictates the addition of α, $\alpha \leq 1$ to the difference Equation 24.2 [Table 1] to represent a diminishing signal. $\beta \leq 1$ in the difference Equation 29 goes a long way in explaining Fig. 17 and $\alpha, \beta \leq 1$ Fig. 18. Diminishing signals help protect the Info-system, the price is that meanwhile, the actual faults avalanche through physical systems, wreaking havoc and, incidentally, also detaching the info-system from reality.
The scale free morphology is manifested in all infrastructure networks on construction, O&M and design. Scale free networks are an outcome of preferential attachment (Barabási & Albert, 1999). Small world nets cause imported risk [Fig. 17]. Scale invariance [], enable the paradigm of autonomous agents being responsible for their scale invariant role, and enable the prevalence of laissez-aller management. Together they facilitates the free exchange of personnel, equipment and sub-contractor between companies and projects, making the whole industry interconnected (Gidado & Wood, 2008). Is the concept of free autonomous agents correct? The information system causes the different trajectories of faults and defects, and the difference between big and small companies. Big companies own the info-system and enjoy 2FB-loops enabled learning (Owen & Koskela, 2006) and the management of faults, while the small companies deal with defects and are destined to subcontracting procedural works. Hence, big companies are modified by learning, each molded by its own complex influences. Small companies are just the same, a product of chance and of the info-system of the big guys. Not only each company is different, but each project is unique, producing a unique information network, and a unique response and calls for a unique attribution of role and responsibility.
The info-system is a Self-Organizing Criticality, the critical parameter portrayed here is the IC. This means that the system self organizes to be barely stable at the IC. Fig. 17 presents the double IC threshold predicted by (Newman & Sneppen, 1996). On construction sites there is one IC for faults and another for defects, the first is in the site info-system and the second is site personnel. On Fig. 17, the info-system IC was traversed, and faults were treated by the second Info-system as defects to the limit

of the second IC, a testament to a phase transition into a metastable state and further on, to avalanche [Fig. 17]. Past the IC, faults are unstoppable, avalanching through the system while inflating, multiplying and infecting other systems. Avalanche changes the morphology, causing phase transition [Fig. 18 (3) type of project transitioned to 19 (1)] and after-shocks (Newman & Sneppen, 1996). On a smaller scale, the move to the left presented in Fig. 7 is the common expectancy in the lifespan of construction projects hinting a self-organizing metastable state past IC thresholds.

QC is the applicator of Filters. The critical role of QC and the devastating potential of QC negligence may lead to an expectation that QC products would relate to all faults. Reality proved otherwise. QC performance is studied on Fig. 19. Fig. 19 (2) shows that QC performance exhibits a clear disparity: some projects are neglected altogether, while QC on project 19 is overzealous. Fig. 19 (1) depicts a small project [project 19] overtakes the entire accumulated effects. Fig. 19 (3) shows that project 19 is not avalanched, on the contrary, its b=1.23 attesting to a fairly well managed project. This particular finding is an outcome of a schism between QC and the contractor. Sociological and personal biased data is a persistent finding.

The literature suggests that design is the paramount fountain of faults, and specifically the large magnitude ones [(Rosenfeld, 2013), Fig. 17]. Fig. 14 portrays design network evolution. The morphology of the net is complex. The complex morphology is manifested in the formation of clusters, bridges and rank Pareto. Rank, clustering and bridge formation are mechanisms generating information overload. Design morphology has bridges that limit information flow for reasons of liability and prestige [Fig. 14 (2)]. Propagation and multiplication of design faults simulated on Fig. 10 by a cellular automata, should be adjusted for preferential attachment morphology that aggravates the produced effects. Combined with laxity of control, and the latency of design faults, propagation and multiplication cause avalanche such as simulated on Fig. 9. BIM amplifies the effects of centrality and convolution [Fig. 8] by the enlargement of the information traffic volume and speed (Jupp, 2017). Designers participate in multiple projects, causing systems to be interconnected, to import risk and rank, causing systemic information faults and the pernicious effects of time [page 10]. Unlike other faults, the products of design are not processed by QC, but rather, enter directly into the information system to be convoluted there [Fig. 8]. Design processes are recursive, aggravating design faults amplification and propagation through the different design disciplines and throughout the project locations and activities. Design is not only a high centrality cluster in the complex information system network [Fig. 13], design generates faulty physical systems where errors are embedded in the physical morphology. Most design errors are latent in the design, manifested only at the stages of construction and operation (Reason, 1990). This fact enables the designers and owners to assign the risk to down-stream companies, thus enjoying risk-free culture. Some design errors are detected by the site info-system before construction commencement, causing friction, extra costs, more time effects, and litigation. Some are detected throughout the construction process, causing avalanches, risk allocation power struggle, and more cost and time overruns. Errors manifest also at the O&M stages.

Change-orders are identical to faults [section 3.3], they change activities and morphology. Prevailing compensations cover direct costs and some overhead, not accounting for the fact that change-orders change the activities [Equation 33], causing time and cost implications, and sometimes even drive activities out of sync, causing clashes and stuttering halts of work and constrained resources. Claims reimbursement should compensate for all implications incurred in and generated by the info-system and compensate for the risk instigated by the added information load.

Having deciphered the modus operandi of complex infrastructure systems as demonstrated in the appendices, for physical systems the like of stormwater systems, DSP control is straight forward. Water level [and hence pressure] gauges are an Integrator and water velocity is a measure of the Proportional of the system. PI and DI controllers may be analogically produced with good effects. It is the complex systems that incorporate humans that pose the utmost challenge. PID was presented here as a simple application that gives some good results. The Integral is indicative of the past [Fig. 17], the proportional of the present [Fig. 9] and the derivative of the future [Fig. 17], thus enabling decision support and action generation. PID was applied here to the faults flux, it may be similarly applied to entropy. These tools potentially transform QC from a system that reports faults to a quality management system.

The universality (Kadanoff, 1990) of ToF was manifested by application to infrastructures from power grids to drainage systems, from complex projects management to maintenance in an office park to safety in municipal buildings and to BIM based design. These applications entail different agents [=nodes in a network model]. Nodes may represent conduits, people, faults, or documents, diverse environments such as construction sites or BIM databases. They comply to different rules of conduct, their barriers vary from code and conduct to physical systems. Yet all are treated with the same equations and the same tools to produce topologically identical networks and outcome. The case-study chosen for this presentation treats a data-base of construction projects. The PDF is log-normal just the same, the magnitude distribution is a power function and the power parameter is within the same margins, where avalanched systems present similar power functions to infrastructure facilities. The avalanche of Fig. 17 presents a similar bifurcation as the Fig. 9 simulation product, and the IC is similar to the one produced in the numerical example of Table 2. The network morphology of Fig. 14 produced by a numerical experiment seems topologically similar to the virtual networks produces in infrastructure systems, design networks and CPM. That is why the same tools are universally applicable.

In pursuit of the research objective, a far larger understanding was gained. Virtual networks of faults are not merely a presentation of risk, they represent the system response, therefore, they provide a means to decipher the physical systems. The physical system generated, such as the stormwater system, differs from the designed systems because effects of sagging, clogging, erosion and uncharted inlets, crosslinks with other systems, and maintenance changed the system beyond recognition.

CONCLUSION

To the theoretical and practical gap in the understanding and management of risk in complex systems, **ToF** contributes a theoretical framework and tools for analysis and management, the development of automated response for infrastructure and the directing of prevention and mitigation actions for projects, design, and maintenance. The acute persistent gap in systemic and behavioral data is addressed by a novel use of faults data banks to generate virtual models. Numerical and Case-studies provided validation and portrayed some applications for real time risk monitoring, and for post factum analysis for research purposes and for claims.

The use of DSP and networks theory with the statistics of complexity to model, to decipher morphology and to predict the behavior of complex systems is a novelty. ToF has been applied to various systems to good effect, showcasing the potential contribution for operation, and for prevention and mitigation.

The development of the power function from the Log-Normal PDF is a contribution of ToF.

Logical agent-based AI is a promising future development.

The effects of complex nets and the limited IC threshold [Fig. 17], the power function effects [3.2] and the emergent traits of risk neglect, the skyrocketing risk [Fig. 9] and correlated risk [Fig. 17], the avalanche and after-shock effects [Fig. 18 and Fig. 14], are all an urgent call for the implementation of mechanisms that would evoke corrective actions directed by means proposed here.

ACKNOWLEGMENT

The authors express their gratitude to SAGIE J.A. for its generous support.

References

Abdul-Aziz, A. (2002). The realities of applying total quality management in the construction industry. *Structural Survey, 20*(Structural Survey, Vol. 20 Iss 2 pp. 88 - 96), 88-96. rg/10.1108/02630800210433864

Albert, R., & Barabasi, A. (2001). Statistical mechanics of complex networks. *Rev. Mod. Phys., 74*(1), 47-97. https://doi.org/10.1103/RevModPhys.74.47

Aljassmi, H., Han, S., & Davis, S. (2014). Project pathogens network: New approach to analyzing construction-defects-generation mechanisms. *Journal of Construction Engineering and Management, 140*(1), 04013028. rg/10.1061/(ASCE)CO.1943-7862.0000774

Bagdiya, N. V., & Wadalkar, S. (2015). Review paper on construction defects. *IOSR J.Mech.Civ.Eng, 12*(2), 88-91. 10.9790/1684-12238891

Barabási, A., & Albert, R. (1999). Emergence of scaling in random networks. *Reviews of Modern Physics, 286*(5439), 509-512. https://www.jstor.org/stable/2899318

Broncano, B., & Vega.E. (2019). A taxonomy of types of epistemic dependence: introduction to the Synthese special issue on epistemic dependence. *Synthese, 197*(7), 2745-2763. rg/10.1007/s11229-019-02233-6

Darren, G., Smith, S., & Dunlop, P. (2005). Lognormal distribution provides an optimum representation of the concrete delivery and placement process. *Journal of Construction Engineering and Management, 131*(2), 230-238. rg/10.1061/(ASCE)0733-9364(2005)131:2(230)

Flyvbjerg, B., Skamris H. Mette K., & Buhl, S. L. (2003). How common and how large are cost overruns in transport infrastructure projects? *Transport Reviews, 23*(1), 71-88. 10.1080/01441640309904

Z Transform- MIT 6.003 Signals and Systems, Fall 2011. Freeman, D. (Director). (2011, 0,0).[Video/DVD] MIT press. 0 https://www.youtube.com/playlist?list=PLUl4u3cNGP61kdPAOC7CzFjJZ8f1eMUxs

Gidado, K., & Wood, H. (2008). An overview of complexity theory and its application to the construction industry. Paper presented at the *Annual ARCOM Conference, , 0* 677-686. https://research.brighton.ac.uk/en/publications/82a15a59-4ba8-4c9e-a5eb-3f294faa1e9d

Haksever, A. M. (2000). A model to predict the occurrence of information overload of project managers [Abstract]. *Proceed. of Int. Conf. on Construction Information,* 13.

Hare, W. (2009). Socratic open-mindedness. *Philosophical Inquiry in Education the Journal of the Canadian Philosophy of Education Societ, 18*(1 2009), 5-16. rg/10.7202/1072334ar

Heron, J., & Reason, P. (1997). A participatory inquiry paradigm. *Qualitative Inquiry, 3*(3), 274-294.

Heyligen, F. (2002). Complexity and self organization. In Phillip A. Laplante (Ed.), *Encyclopedia of Information Systems and Technology* (2008th ed., pp. 250-260). CRC Press. no

Horvath, W. J. (1959). Applicability of the lognormal distribution to servicing times in congestion problems. *Operations Research, 7*(1), 126-128.

Hosny, A., Nik-Bakht, M., & Moselhi, O. (2020). Workspace planning in construction: non-deterministic factors. *Automation in Construction, 116*, 103222. rg/10.1016/j.autcon.2020.103222

Ilozor, B. D., Okoroh, M. I., & Egbu, C. E. (2004). Understanding residential house defects in Australia from the State of Victoria. *Building and Environment, 39*(3), 327-337. https://doi.org/10.1016/j.buildenv.2003.07.002

Jupp, J. (2017). 4D BIM for environmental planning and management. *Procedia Engineering, 180*, 190-201. 10.1016/j.proeng.2017.04.178

Kadanoff, L. P. (1990). Scaling and universality in statistical physics. *Physica A: Statistical Mechanics and its Applications, 163*(1), 1-14.

Kadanoff, L. P., Nagel, S. R., Wu, L., & Zhou, S. (1989). Scaling and universality in avalanches. *Physical Review A, 39*(12), 6524.

Lopez, R., Love, P. E., Edwards, D. J., & Davis, P. R. (2010). Design error classification, causation, and prevention in construction engineering. *Journal of Performance of Constructed Facilities, 24*(4), 399-408.

Love, P. E., Lopez, R., Edwards, D. J., & Goh, Y. M. (2012). Error begat error: Design error analysis and prevention in social infrastructure projects. *Accident Analysis & Prevention, 48*, 100-110.

Miller, G. (1957). Some effects of intermittent silence. *The American Journal of Psychology, 70*(2), 311-314.

Mills, A., Love, P. E., & Williams, P. (2009). Defect Costs in Residential Construction. *Journal of Construction Engineering and Management, 135*(1), 12-16. 10.1061/(ASCE)0733-9364(2009)135:1(12)

Müller, R., & Jugdev, K. (2012). Critical success factors in projects: Pinto, Slevin, and Prescott-the elucidation of project success. *International Journal of Managing Projects in Business, 5*(4), 757-775. rg/10.1108/17538371211269040

Newman, M. (2005). Power laws, Pareto distributions and Zipf's law. *Contemporary Physics, 46*(5), 323-351. 10.1080/00107510500052444

Newman, M., & Sneppen, K. (1996). Avalanches, scaling, and coherent noise. *Physical Review E, 54*(6), 6226. https://journals-aps-org.ezproxy.bgu.ac.il/pre/pdf/10.1103/PhysRevE.54.6226

Owen, R., & Koskela, L. (2006). An agile step forward in project management. Paper presented at the *2nd Specialty Conference on Leadership and Management in Construction and Engineering,* 216-224. SBN 0-9707869-1-3 https://www.academia.edu/download/30726360/FinalProceedings.pdf#page=223

Pinto, J. K., & Slevin, D. P. (1987). Critical factors in successful project implementation. *IEEE Transactions on Engineering Management, 1*(1), 22-27.

Reason, J. (1990). The contribution of latent human failures to the breakdown of complex systems. *Philosophical Transactions of the Royal Society of London.B, Biological Sciences, 327*(1241), 475-484.

Reason, J. (1995). Understanding adverse events: human factors. *BMJ Quality & Safety, 4*(2), 80-89.

Rokooei, S. (2015). Building Information Modeling in Project Management: Necessities, Challenges and Outcomes. *Procedia - Social and Behavioral Sciences, 210*(0), 87-95. 10.1016/j.sbspro.2015.11.332

Rosenfeld, Y. (2013). Root cause analysis of construction cost overruns. *Journal of Construction Engineering and Management, 10.1061*(1943), 7862. 10.1061/(ASCE)CO .1943-7862.0000789.

Söderlund, J. (2004). Building theories of project management: past research, questions for the future. *International Journal of Project Management, 22*(3), 183-191. rg/10.1016/S0263-7863(03)00070-X

Streufert, S. C. (1973). Effects of information relevance on decision making in complex environments. *Memory & Cognition, 1*(3), 224-228. 0

Thomas, H. R., Horman, M. J., De Souza, U. E. L., & Zavřski, I. (2002). Reducing variability to improve performance as a lean construction principle. *Journal of Construction Engineering and Management, 128*(2), 144-154.

Tinós, R., & Yang, S. (2007). A self-organizing random immigrants genetic algorithm for dynamic optimization problems. *Genetic Programming and Evolvable Machines, 8*(3), 255-286. 0

Trigo, T. (2019). *Numerical Signal Processing* (pre ed.). TAU University SCE college. no

Yonat, N., & Shohet, I. M. (2022). *CPM Stability in Complex Projects and Systems*. Open Engineering Inc. 10.31224/2562

Appendix A- Numerical experiments

In this section three numerical experiments are reported. The first is a time dependent Markovian process of a second degree with no correction mechanism, the second is a cellular automata with a simple grid and spatial and temporal correlation with a randomness additive. The third is a numerical experiment with an eigenvalues vector given a quantity probability and power function generated scaling. This vector propagates in a system a few numbers of DT [Discrete Time] iteration, to produce a system collapse. The next experiment is an info-net self-organization in response to a Redo order.

A1. DT numerical experiment with randomness and no correction mechanism

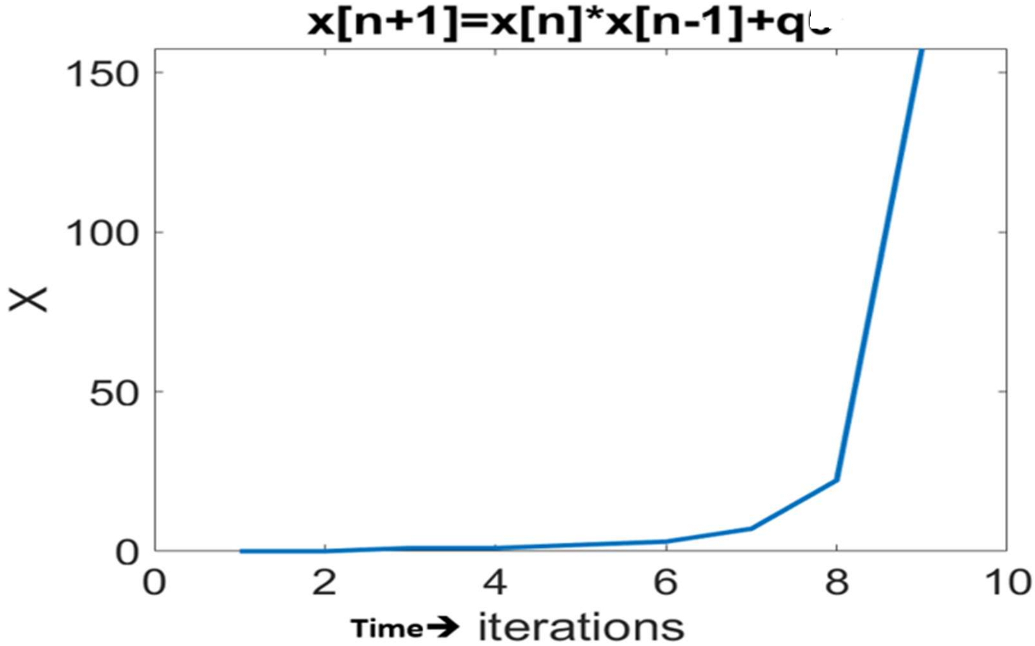


Fig. 9. Time affects via repetitions [“bifurcation”]. q0=0.002

A2. Cellular automata

a bounded random walk.

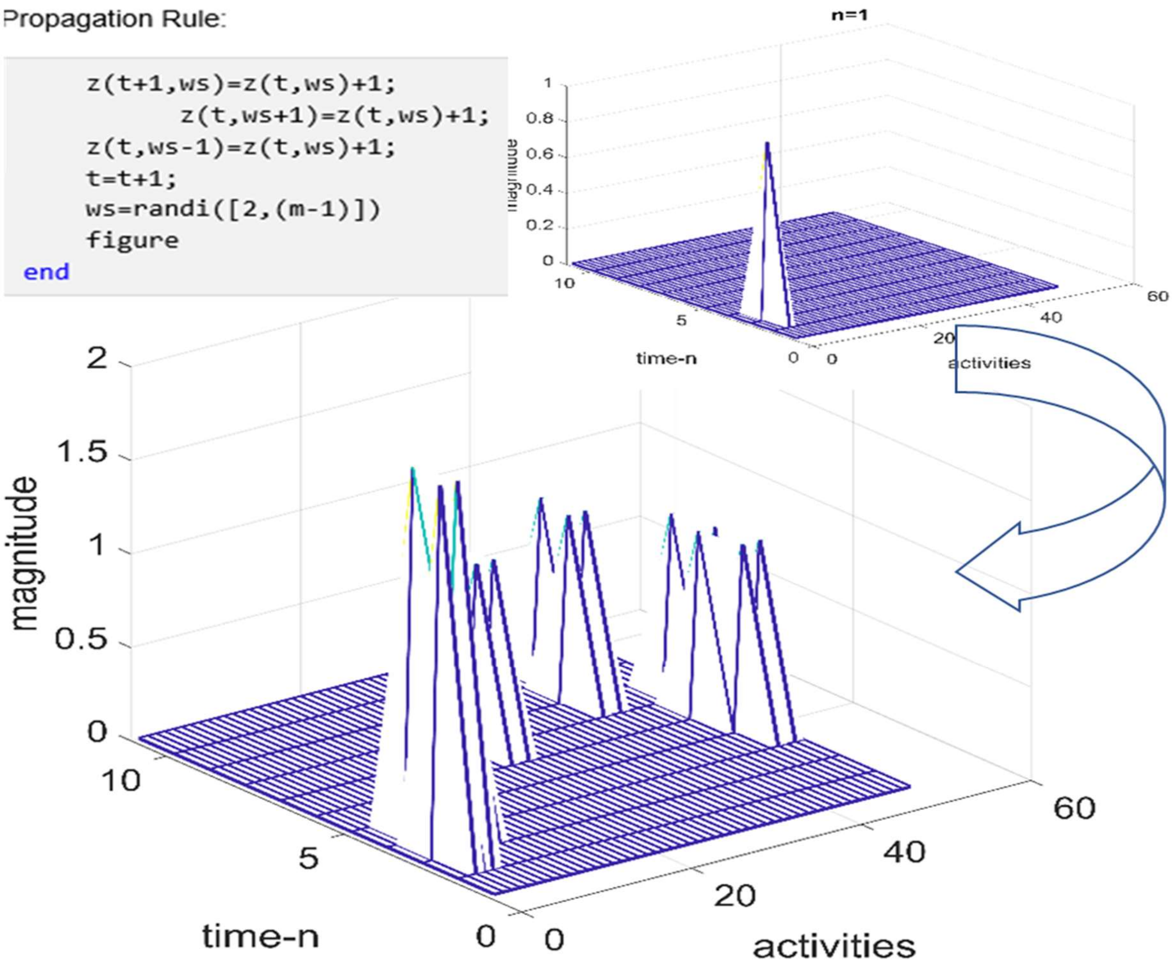


Fig. 10. Cellular automata iteration 7

A3. Numerical experiment

Relying on the Proposition developed on chapter 3, an error signal with a magnitude that surpass the IC causes an avalanche.

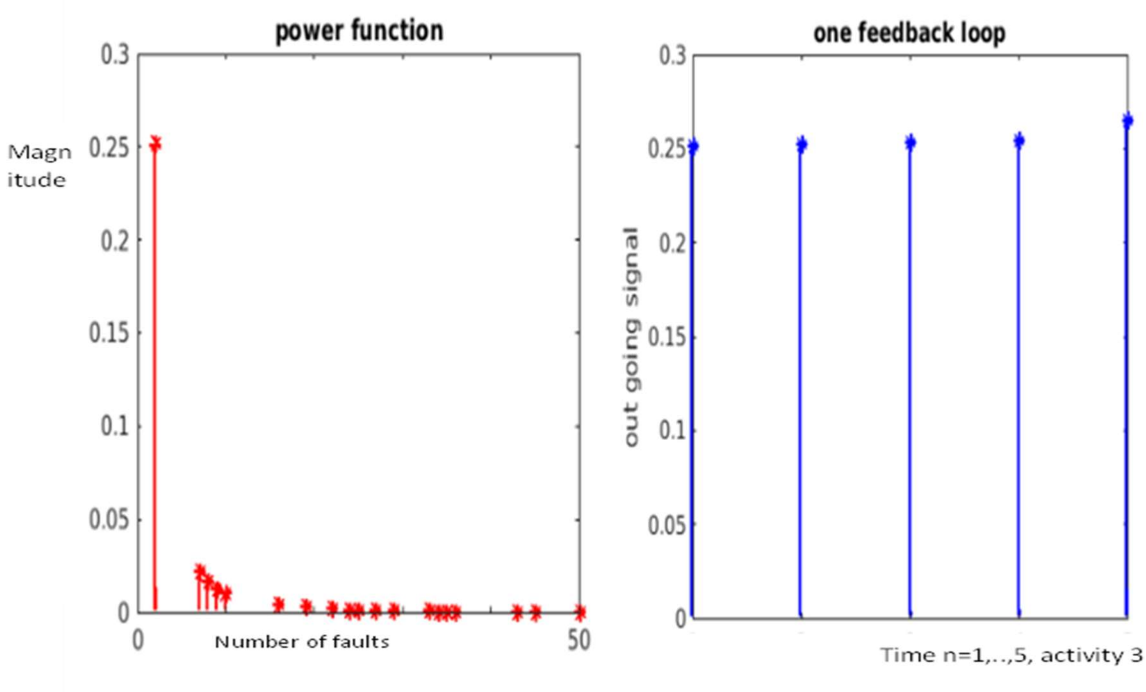


Fig. 11. 1FB loop amplification of extreme event, the entering power function (left) and the amplification (right).

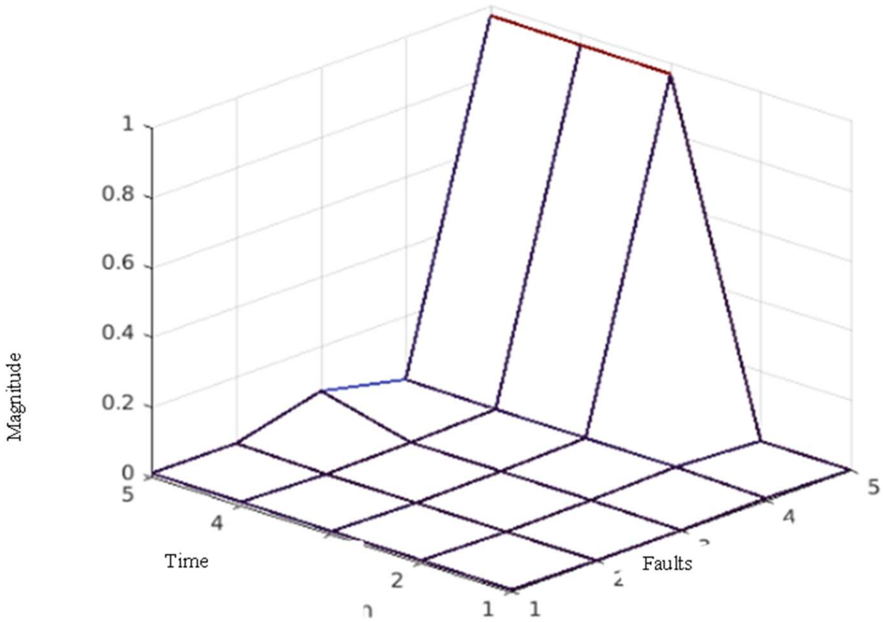


Fig. 12 1FB loop amplification of an extreme event

TABLE 2. 2FB loops random iterations:

	1	2	3	4	5	Total
	0.0013	0.0007	0.0297	0.0013	0.0135	0.0465
2	0.0079	0.0012	0.0302	0.253	0.0159	0.3082
3	0.0142	0.0027	0.0605	0.2567	0.0717	0.4058
4	0.0233	0.0073	0.0915	0.5141	0.0888	0.725
5	0.0431	0.0113	0.15577	0.7843	0.1625	1.15697

1FB loop adds little to the overload and for defects its effect is negligible. Even with big event the accumulation rarely causes overflow. 2FB loop [columns 4,5] inevitably causes avalanche unless treated. Coupled with events of high magnitude [column 4], the effect is rapid.

A4. Information net Morphology and transformation

In this section rank power function is demonstrated, it is a product of preferential attachment. It is shown here that this function is modified by faults. The rank K of nodes N is $N(K) \sim K^{-a}$ (Barabási & Albert, 1999). The number of connections [K] of the company hub [noted “GC” in the graph] is proportional to the number of nodes, while the site info-system [“SE”] has a higher rank, therefore a<=3. On Fig. 14 curve fitting yielded a=-1.523 [R^2=0.9365].

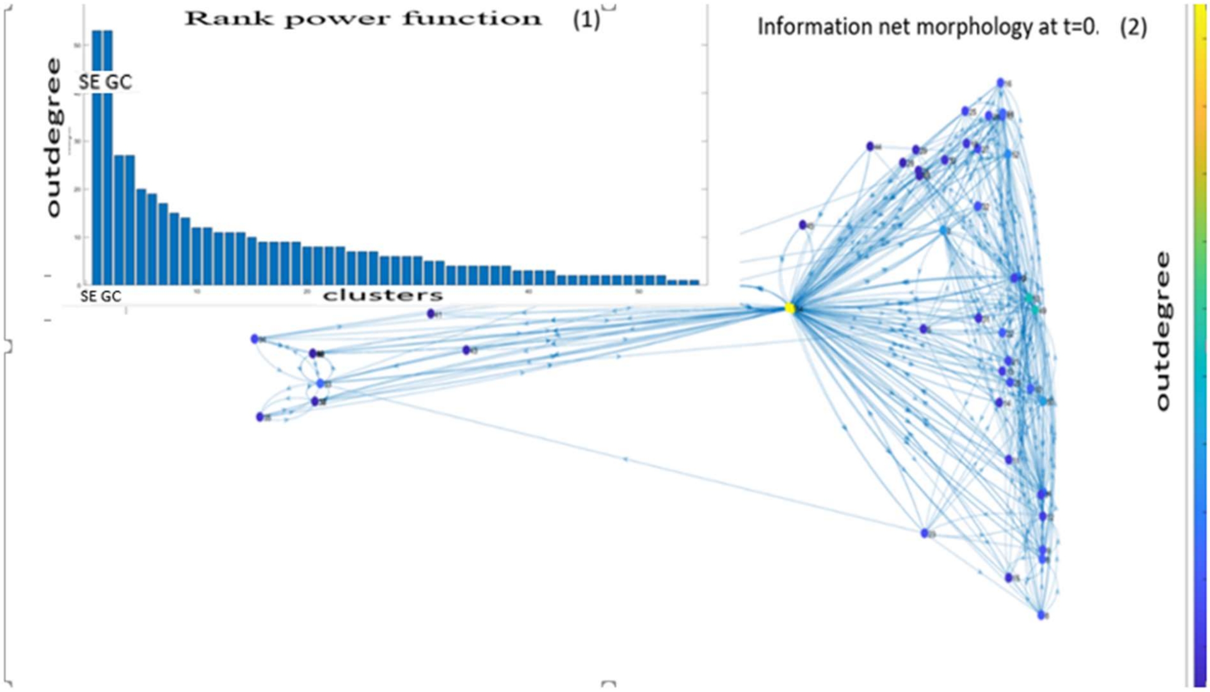


Fig. 13. Information net morphology at t=0. Nodes represent autonomous agents [such as designers and sub-contractors]. Nodes degree distribution rank is a power function [13.1], therefore, the net is scale-free.

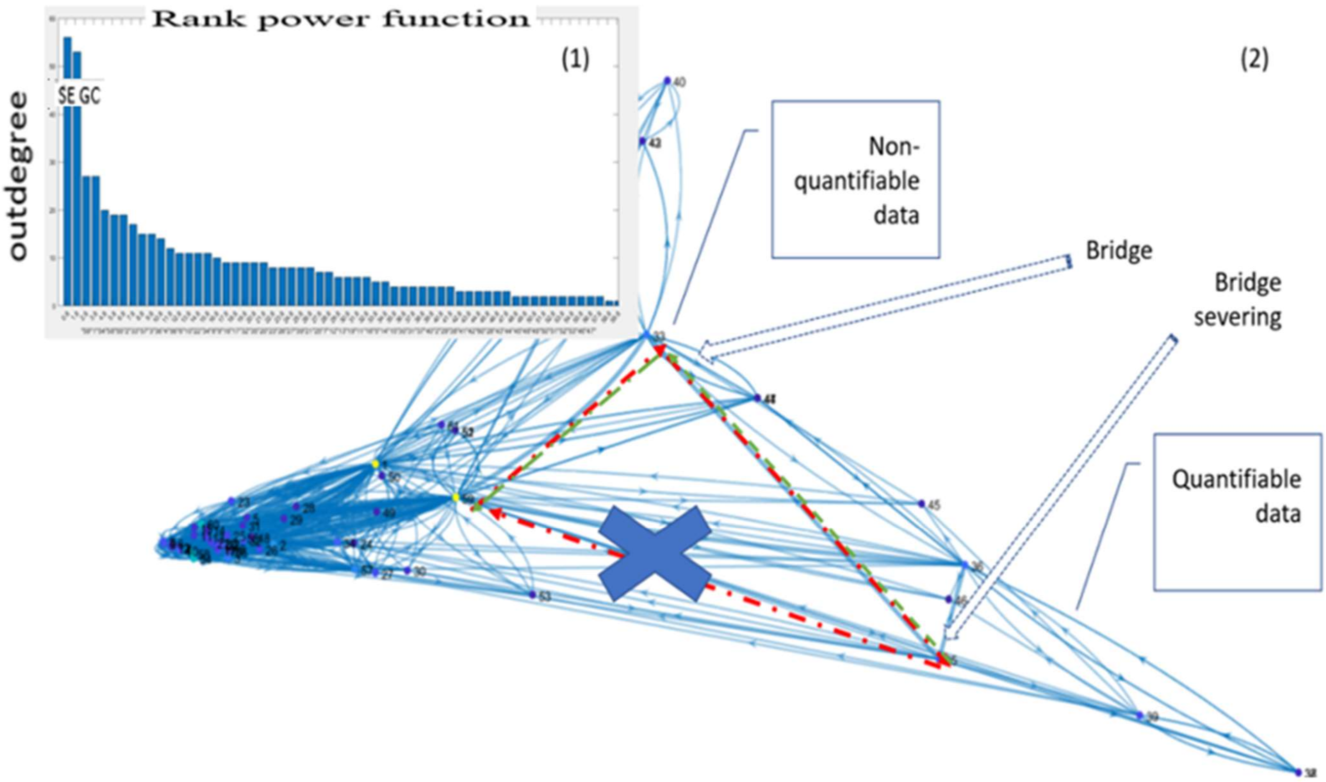


Fig. 14. Information morphology evolution after a redo order originated in a design error. Rank is changed [14.1], the centrality of site system emerges, the weight of edges is changed, triadic connections are severed, and bridges formed [14.2].

Appendix B – Case study

In this section the results of an analysis performed on a database of 27+1 projects is laid out.
The projects are of tens to hundreds of million $. The number of faults is about 7100.
The extent of the database is 8 years.
The analysis follows the methodological sequence: PDF, Power function, DSP and descriptive statistics analysis, IC assessments, time and morphology.
The Barriers are the Code, the contracts, the praxis [best practice], inspection practices, testing labs.
QC provided a list of faults. Its products and quality of output varied between projects and with time.
Biased sampling is a common phenomenon in the construction industry and the analysis factors it in.
Having assured that the database is under log-normal probability [Fig. 15], power functions were machine fitted to each project. The resulting functions were compared [within the limitations of the data] to Fig. 4 procedure projections. Those projects that deviate from the expectations are of interest, in this database, project 1 is of interest. Project 1 is correlated with projects 22, 23 [Fig. 17].

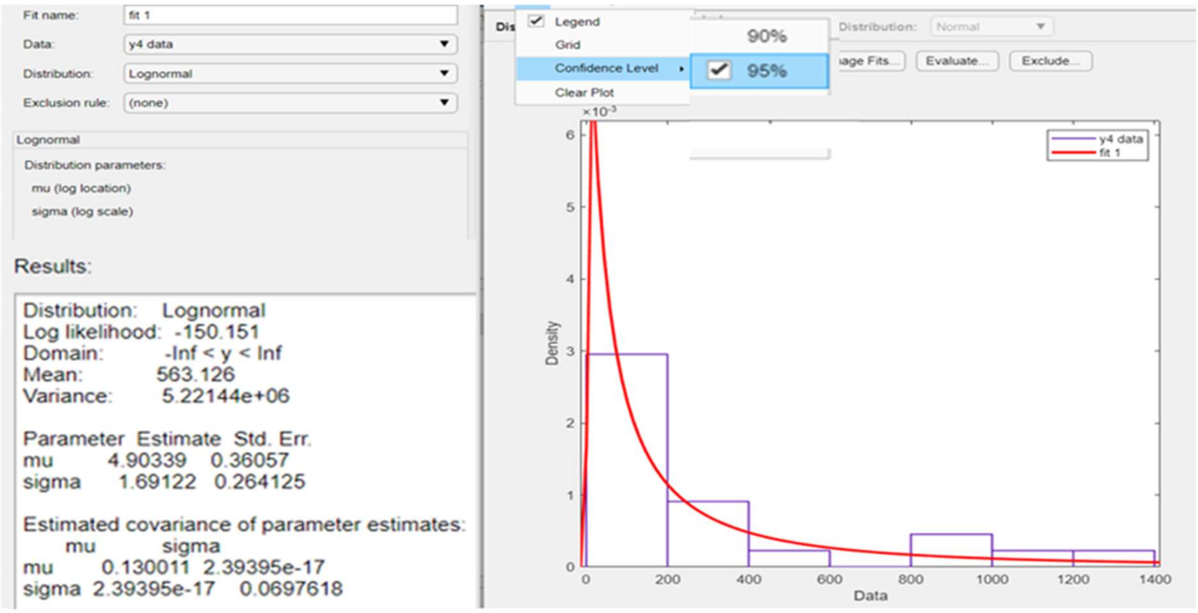


Fig. 15. PDF for 27 projects [95%confidence level], bins=18

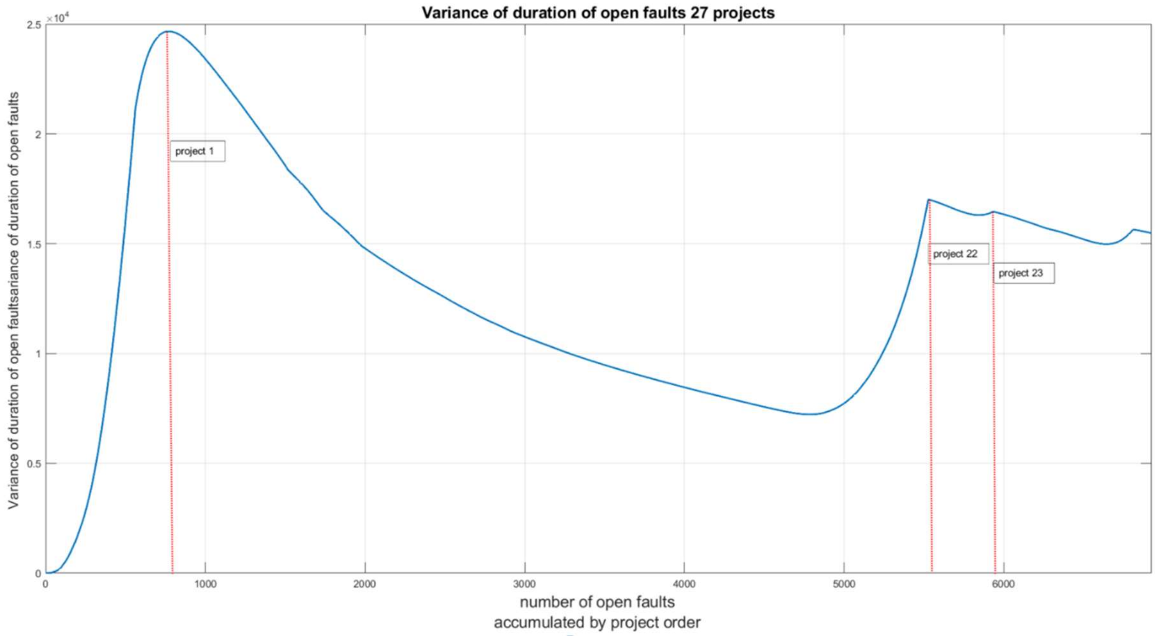
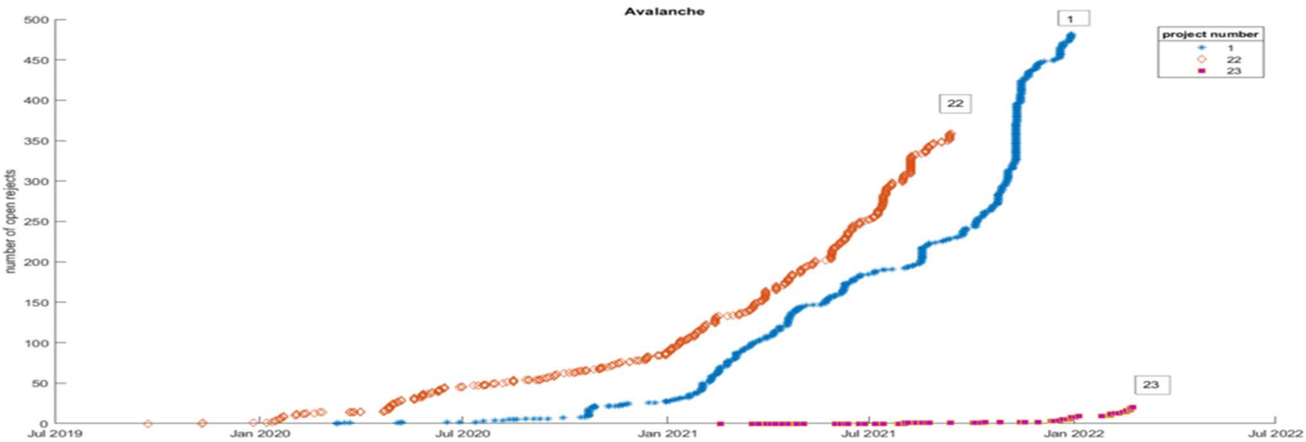


Fig. 16. Cumulative variance of 27 projects, accumulated by order of projects. The magnitude of avalanche goes to infinity, thus the mean and stdv.



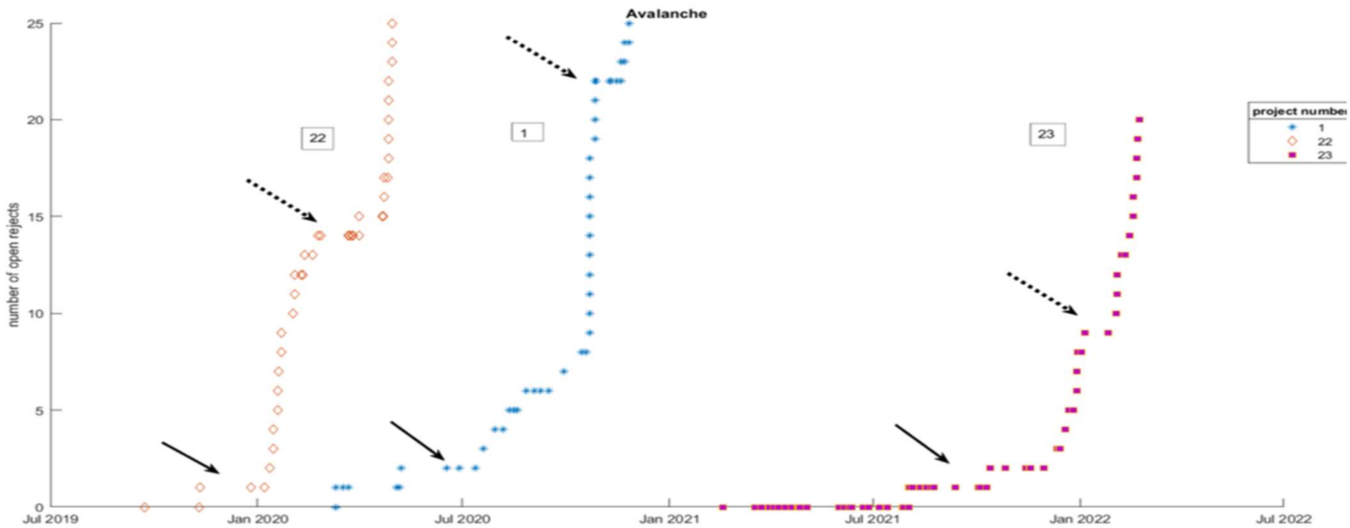


Fig. 17. The integral of open rejects for three "light" train projects: Project "1"- civil engineering works, Project "22"- systems and project "23"– control. The bottom blown out part – the IC [the bifurcation point, marked by arrows] and second IC [marked by dashed arrows].

As faults started on the "systems" [22] project, prior to the construction works [1], it is evident that the three projects are not correlated via construction faults. The influencing factor is design. This is a design generated avalanche.

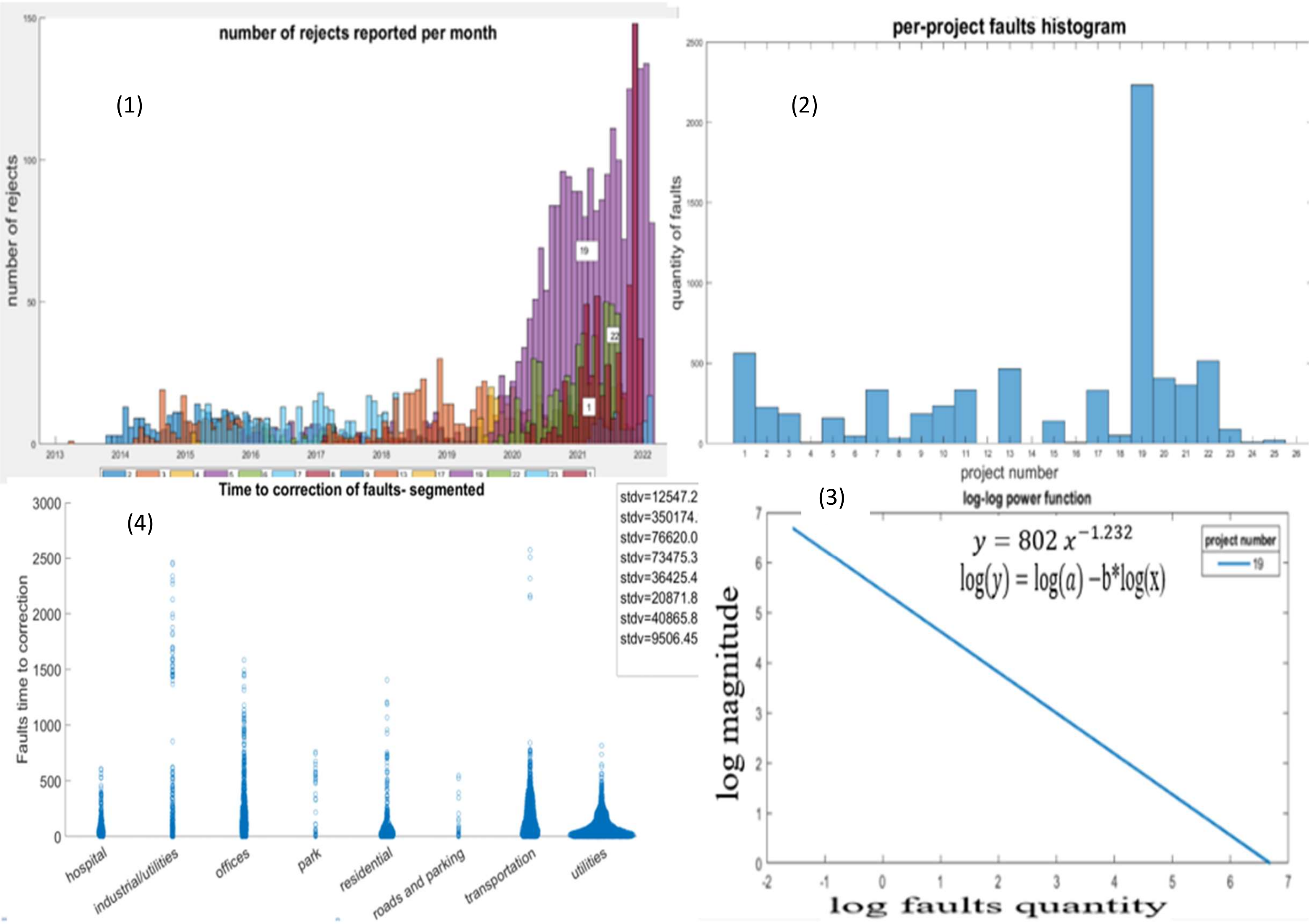


Fig. 18. clockwise: 18.1 superposed graphs of number of faults, 18.2 the total number of faults per project, 18.3 log-log power function of project 19 showing an avalanche of defects, 18.4 segmented time to correction of faults and their stdv.

Fig. 18 (4) is an indication to segmentation. The nominal number of faults is incidental, it is the scatter pattern that is of interest. In this data set, the significance of this observation may be somewhat dubious owing to the high stdv of industrial/utilities segment; that may indicate erroneous segmentation. Moreover, the high stdv values of specific projects manifested on Fig. 16 are not reflected in Fig. 18 (4) segments stdv, this is an indication for segmentation because within a segment stdv is considerably low.

High duration until closure of QC-rejects is an indication to faults magnitude and oftentimes to bad QC management and contract breach [Fig. 20].

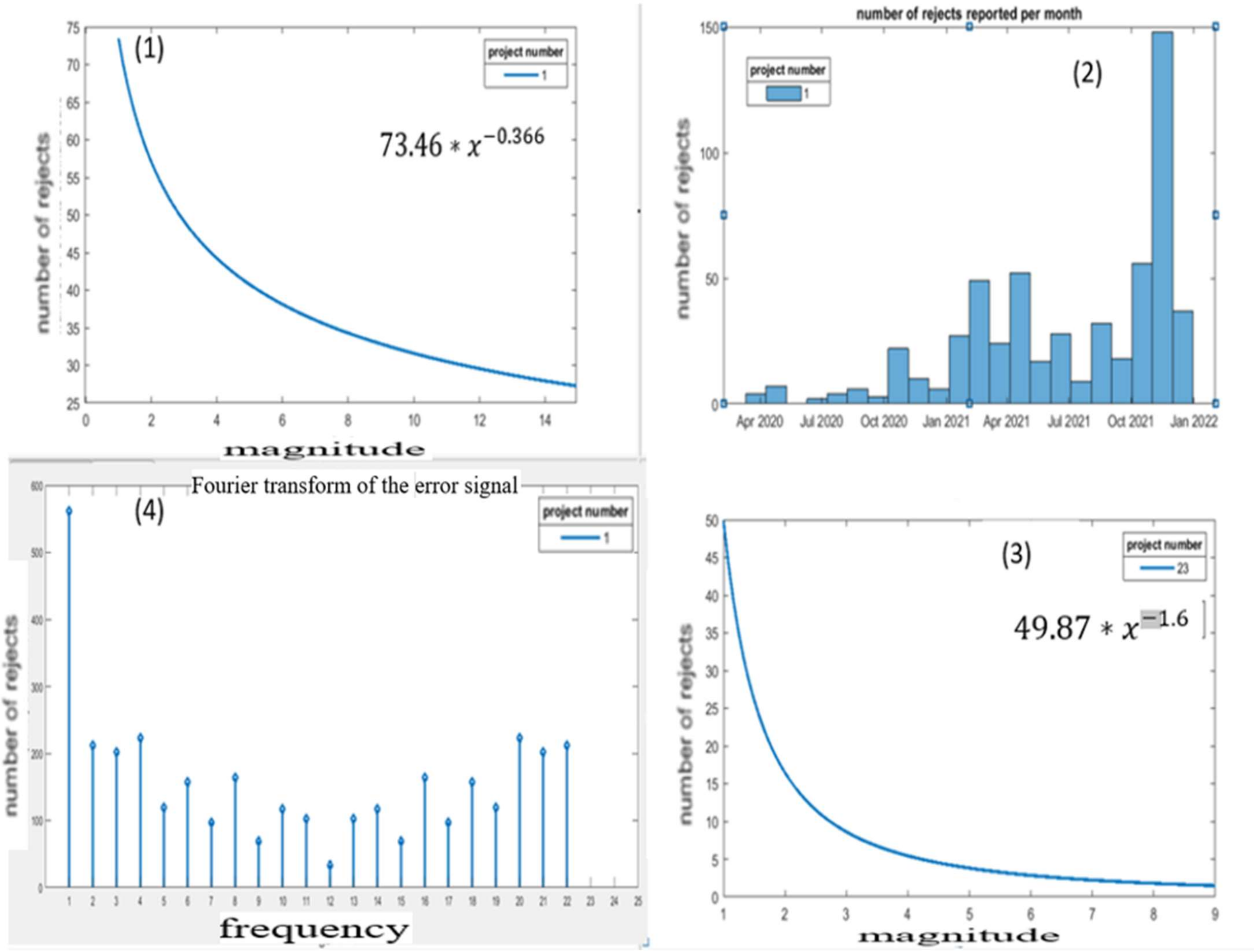


Fig. 19. Power function for the avalanched projects [19.1] where “a” factors the magnitude to the relevant scale [compare to Fig. 5, for “a” =ac^{-b}]. The histogram [19.2] pinpoints the time of avalanche, the Fourier transform of the error signal [19.4] shows white noise traits of frequency. The sinusoidal magnitude is a consistent phenomenon in our case-studies. A move from 19.3 to 19.1 function is a phase transition.

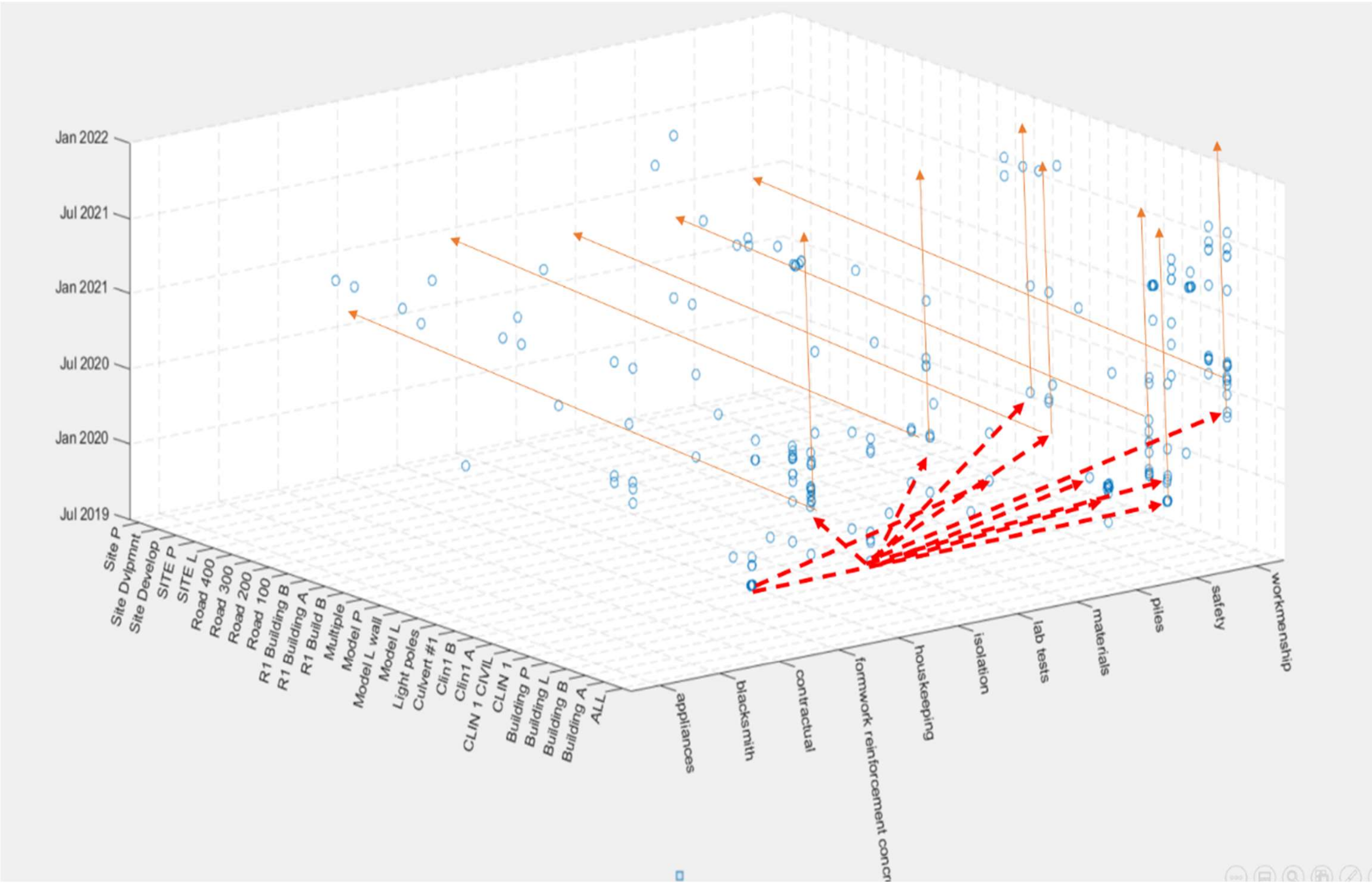


Fig. 20. A storage facility 3D scatter plot- causal spatio-temporal with a fault propagation trajectory [added manually using the deficiency list natural language description]

References

Abdul-Aziz, A. (2002). The realities of applying total quality management in the construction industry. *Structural Survey, 20*(Structural Survey, Vol. 20 Iss 2 pp. 88 - 96), 88-96. rg/10.1108/02630800210433864

Albert, R., & Barabasi, A. (2001). Statistical mechanics of complex networks. *Rev. Mod. Phys., 74*(1), 47-97. https://doi.org/10.1103/RevModPhys.74.47

Aljassmi, H., Han, S., & Davis, S. (2014). Project pathogens network: New approach to analyzing construction-defects-generation mechanisms. *Journal of Construction Engineering and Management, 140*(1), 04013028. rg/10.1061/(ASCE)CO.1943-7862.0000774

Bagdiya, N. V., & Wadalkar, S. (2015). Review paper on construction defects. *IOSR J.Mech.Civ.Eng, 12*(2), 88-91. 10.9790/1684-12238891

Barabási, A., & Albert, R. (1999). Emergence of scaling in random networks. *Reviews of Modern Physics, 286*(5439), 509-512. https://www.jstor.org/stable/2899318

Broncano, B., & Vega.E. (2019). A taxonomy of types of epistemic dependence: introduction to the Synthese special issue on epistemic dependence. *Synthese, 197*(7), 2745-2763. rg/10.1007/s11229-019-02233-6

Darren, G., Smith, S., & Dunlop, P. (2005). Lognormal distribution provides an optimum representation of the concrete delivery and placement process. *Journal of Construction Engineering and Management, 131*(2), 230-238. rg/10.1061/(ASCE)0733-9364(2005)131:2(230)

Flyvbjerg, B., Skamris H. Mette K., & Buhl, S. L. (2003). How common and how large are cost overruns in transport infrastructure projects? *Transport Reviews, 23*(1), 71-88. 10.1080/01441640309904

Z Transform- MIT 6.003 Signals and Systems, Fall 2011. Freeman, D. (Director). (2011, 0,0).[Video/DVD] MIT press. 0 https://www.youtube.com/playlist?list=PLUl4u3cNGP61kdPAOC7CzFjJZ8f1eMUxs

Gidado, K., & Wood, H. (2008). An overview of complexity theory and its application to the construction industry. Paper presented at the *Annual ARCOM Conference, , 0* 677-686. https://research.brighton.ac.uk/en/publications/82a15a59-4ba8-4c9e-a5eb-3f294faa1e9d

Haksever, A. M. (2000). A model to predict the occurrence of information overload of project managers [Abstract]. *Proceed. of Int. Conf. on Construction Information,* 13.

Hare, W. (2009). Socratic open-mindedness. *Philosophical Inquiry in Education the Journal of the Canadian Philosophy of Education Societ, 18*(1 2009), 5-16. rg/10.7202/1072334ar

Heron, J., & Reason, P. (1997). A participatory inquiry paradigm. *Qualitative Inquiry, 3*(3), 274-294.

Heyligen, F. (2002). Complexity and self organization. In Phillip A. Laplante (Ed.), *Encyclopedia of Information Systems and Technology* (2008th ed., pp. 250-260). CRC Press. no

Horvath, W. J. (1959). Applicability of the lognormal distribution to servicing times in congestion problems. *Operations Research, 7*(1), 126-128.

Hosny, A., Nik-Bakht, M., & Moselhi, O. (2020). Workspace planning in construction: non-deterministic factors. *Automation in Construction, 116*, 103222. rg/10.1016/j.autcon.2020.103222

Ilozor, B. D., Okoroh, M. I., & Egbu, C. E. (2004). Understanding residential house defects in Australia from the State of Victoria. *Building and Environment, 39*(3), 327-337. https://doi.org/10.1016/j.buildenv.2003.07.002

Kadanoff, L. P. (1990). Scaling and universality in statistical physics. *Physica A: Statistical Mechanics and its Applications, 163*(1), 1-14.

Kadanoff, L. P., Nagel, S. R., Wu, L., & Zhou, S. (1989). Scaling and universality in avalanches. *Physical Review A, 39*(12), 6524.

Lopez, R., Love, P. E., Edwards, D. J., & Davis, P. R. (2010). Design error classification, causation, and prevention in construction engineering. *Journal of Performance of Constructed Facilities, 24*(4), 399-408.

Love, P. E., Lopez, R., Edwards, D. J., & Goh, Y. M. (2012). Error begat error: Design error analysis and prevention in social infrastructure projects. *Accident Analysis & Prevention, 48*, 100-110.

Miller, G. (1957). Some effects of intermittent silence. *The American Journal of Psychology, 70*(2), 311-314.

Mills, A., Love, P. E., & Williams, P. (2009). Defect Costs in Residential Construction. *Journal of Construction Engineering and Management, 135*(1), 12-16. 10.1061/(ASCE)0733-9364(2009)135:1(12)

Müller, R., & Jugdev, K. (2012). Critical success factors in projects: Pinto, Slevin, and Prescott-the elucidation of project success. *International Journal of Managing Projects in Business, 5*(4), 757-775. rg/10.1108/17538371211269040

Newman, M. (2005). Power laws, Pareto distributions and Zipf's law. *Contemporary Physics, 46*(5), 323-351. 10.1080/00107510500052444

Newman, M., & Sneppen, K. (1996). Avalanches, scaling, and coherent noise. *Physical Review E, 54*(6), 6226. https://journals-aps-org.ezproxy.bgu.ac.il/pre/pdf/10.1103/PhysRevE.54.6226

Owen, R., & Koskela, L. (2006). An agile step forward in project management. Paper presented at the *2nd Specialty Conference on Leadership and Management in Construction and Engineering,* 216-224. SBN 0-9707869-1-3 https://www.academia.edu/download/30726360/FinalProceedings.pdf#page=223

Pinto, J. K., & Slevin, D. P. (1987). Critical factors in successful project implementation. *IEEE Transactions on Engineering Management, 1*(1), 22-27.

Reason, J. (1990). The contribution of latent human failures to the breakdown of complex systems. *Philosophical Transactions of the Royal Society of London.B, Biological Sciences, 327*(1241), 475-484.

Reason, J. (1995). Understanding adverse events: human factors. *BMJ Quality & Safety, 4*(2), 80-89.

Rokooei, S. (2015). Building Information Modeling in Project Management: Necessities, Challenges and Outcomes. *Procedia - Social and Behavioral Sciences, 210*(0), 87-95. 10.1016/j.sbspro.2015.11.332

Rosenfeld, Y. (2013). Root cause analysis of construction cost overruns. *Journal of Construction Engineering and Management, 10.1061*(1943), 7862. 10.1061/(ASCE)CO .1943-7862.0000789.

Söderlund, J. (2004). Building theories of project management: past research, questions for the future. *International Journal of Project Management, 22*(3), 183-191. rg/10.1016/S0263-7863(03)00070-X

Streufert, S. C. (1973). Effects of information relevance on decision making in complex environments. *Memory & Cognition, 1*(3), 224-228. 0

Trigo, T. (2019). *Numerical Signal Processing* (pre ed.). TAU University SCE college. no

Yonat, N., Isaak, S., & Shohet, I. (2022). Complex Infrastructure Systems Analysis and Management, a Case-Study.

Yonat, N., & Shohet, I. M. (2022). *CPM Stability in Complex Projects and Systems*. Open Engineering Inc. 10.31224/2562