Theory of Faults (ToF)

Digital Statistic Quality Control in Complex Systems

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ABSTRACT

ToF deciphers the traits, morphology, and modus operandi of complex systems. The epistemic reliance of projects and facilities on information, supports a proposition that the cause of faults and catastrophes is rooted in information management. From this, a theoretical system, **TOF**, is developed mathematically, expanded by numerical experiments, validated by database analysis, and extended to sociological consequences using participatory inquiry paradigm.

TOF is applicable for systems characterized by a Log-normal PDF. A power function magnitude distribution is developed from the Log-normal PDF. Effects of the power function such as avalanche, and emergent traits such as segmentation and risk affiliation are expounded. DSP [**D**igital **S**ignal **P**rocessing] analysis broadens the understanding of the effects of time and morphology, such as faults multiplication and propagation, and cost and time overruns. QC in its role as DSP filters instigator, the information system failures generation mechanism via overloaded scale free nets, and the barriers and their effects on conservatism, are portrayed.

The application of the theoretical system with DSP and descriptive statistics tools, enables the development of automated responses in infrastructure, and in social systems, sustains behavioral and contractual preventive and corrective means. ToF facilitates digital quality control, supports research, claims, block-chain contracts, and the development of logical agent AI.

KEYWORDS

Complex Project, Construction Defects, Risk Management, Quality Control, Time and Cost.

1. 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 distributions [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). In these cases, the systems are chaotic. The log-normal probability distribution is not a rare occurrence, it best fits most construction projects, infrastructure operation and maintenance. The log-normal PDF leads to phenomena of chaos, rendering the common managerial tools inefficient. The butterfly effect for one, stands for small perturbations that cause high effects down-stream, disrupts supply chains, generates emergent behaviors, such as avalanche, and renders meticulous time management software aided efforts ineffective. Some other effects are complex nets' imported risk, system robustness that hinders change efforts, Black-swan effect that stands for unprecedented events, to name but a few.

The research objective is to provide a mathematical model to risk in chaotic systems, deliver numerical analysis and predictions and to provide computational, automated, when possible, means to address risk. There is a gap in the understanding of the origin and inception of faults in construction (Bagdiya & Wadalkar, 2015), (Söderlund, 2004). The literature suggests an information epistemological origin

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(Streufert, 1973), (Haksever, 2000) and information overload as a cause of collapse, (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 [for the shortcoming of: JIT (Thomas et al., 2002), 6-sigma (Han et al. 2008), BIM (Jupp, 2017), uncertainty management (Rokooei, 2015)]. Neuron system-based AI fails in complex systems because the long tail of the power function [Figure 4], draws inference to the low impact occurrences, the factors are covariates [Figure 10], rendering Markovian assumption wrong, and because same projects complex adaptive systems generate different emergent behaviors and various outcomes [Figure 19.2]. Moreover, there is a gap in reliable data (Lopez et al., 2010).

In this article, the gaps are addressed with a concise theory [ToF], a database and a set of tools.

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. QC produced lists of faults are digitized to generate a propagating error signal that is fed into the information system. This info-system has a limit to its capacity [called here **IC**], that makes the outcome a threshold phenomenon. This system is modeled as a complex communication net. The control signal generation facilitates numerical experiments that elucidate the mathematical presentation and support the understanding of the role of the influencing factors. Time and morphology influence is further examined using complex nets. Using descriptive statistics and DSP [digital signal processing], a fault database is case studied to support and validate the theoretic findings. Practical knowledge places the findings in the reality of projects and infrastructure. Prevention and mitigation strategies are discussed and a novel **PID** [**P**roportional **I**ntegral **D**erivative] application is suggested and applied in the case studied. PID is a basic DSP controller that operates on the Proportional, Integral and Derivative of the error signal. The graphical abstract [Figure 1] tracks the trajectory of faults in projects and facilities.

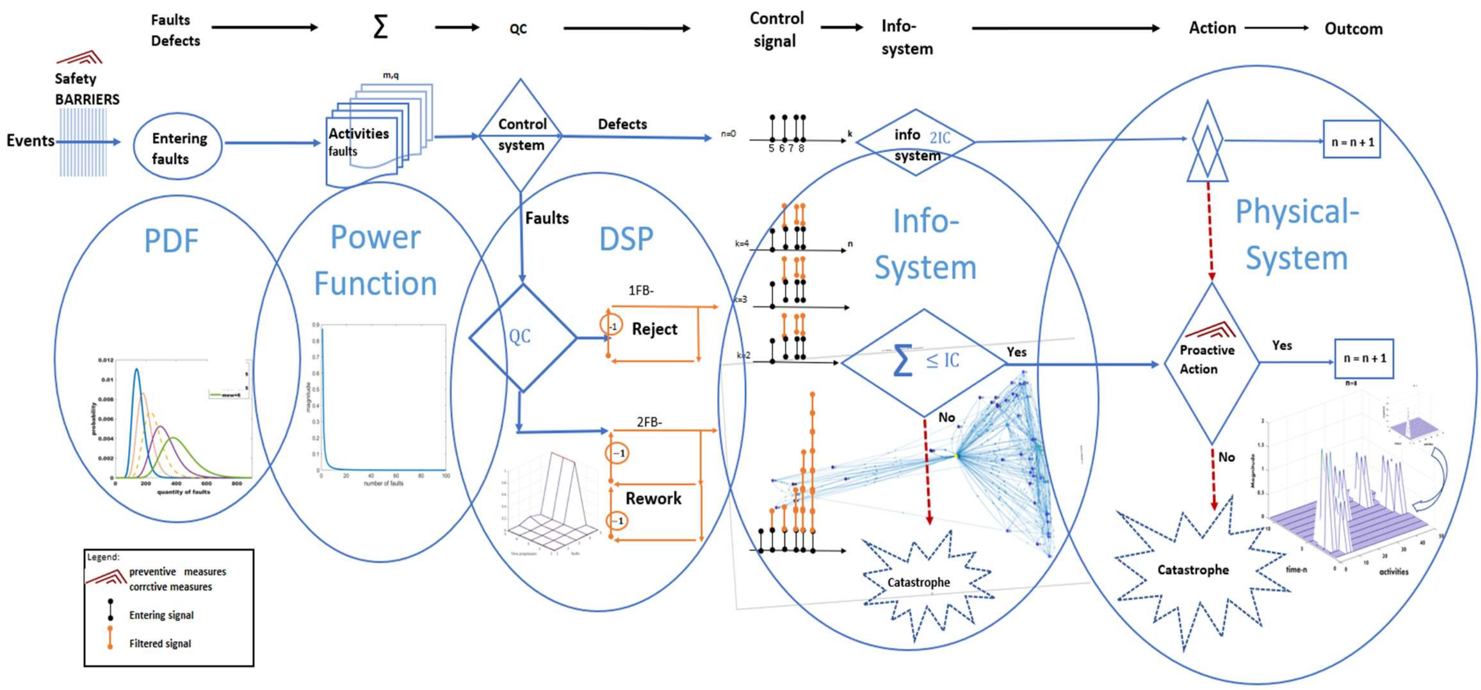

FIGURE 1. Fault progression through a system

2. METHODOLOGY

The article's framework [Figure 2] follows the progression of faults [Figure 1]. PDF, Power function, DSP and the info-system are presented in this order followed by the supporting factors, - Time, and Morphology. Next, the Barriers and preventive and corrective measures are laid out. QC role is described in relation to DSP and in the database study. The presentation is mathematic. Numerical simulations and experiments results are presented In Appendix A. Database-study results are reported on Appendix B. In the discussion section, "practical knowing" which is a participatory inquiry paradigm (Heron & Reason, 1997) maps all these to the realities of construction sites and infrastructure projects. DSP tools are presented in the results section 3, used in the simulation appendix A, and used along-side descriptive statistics in the case-study on Appendix B.

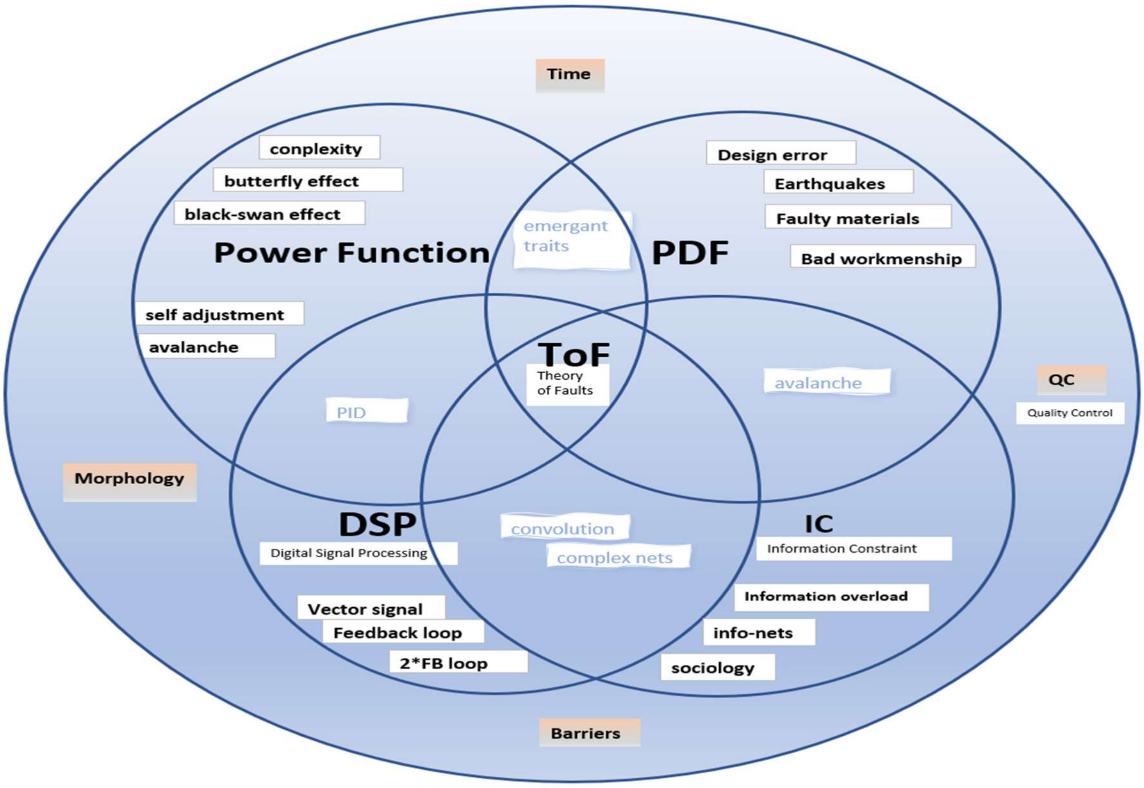

FIGURE 2. Fault space

3. RESULTS

Proposition: The cause of faults and catastrophes in the physical world are failures in the information system. There is an epistemic reliance of the systems on information, and the info-system is the source of the information, therefore information generated faults are originated in the info-system. The opposite sentence, that the information is the only cause of faults is an outcome of the role of the barriers and QC [Figure 1] that arrests all possibility of faults not being information faults. When IC is traversed, faults multiply and propagate unstopped to avalanche and catastrophe.

3.1. PDF

The Log-normal PDF [Figure 3] is presented here by Equations 1-6 and Figure 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)
$\text{Median (X)} = e^{\mu}$ (4)
$Mode(X) = e^{\mu-\sigma^2}$ (5)
$x = e^{\mu+z*\sigma} \quad x \in X$ (6)
where z=ln(x) is normally distributed N(μ, σ).

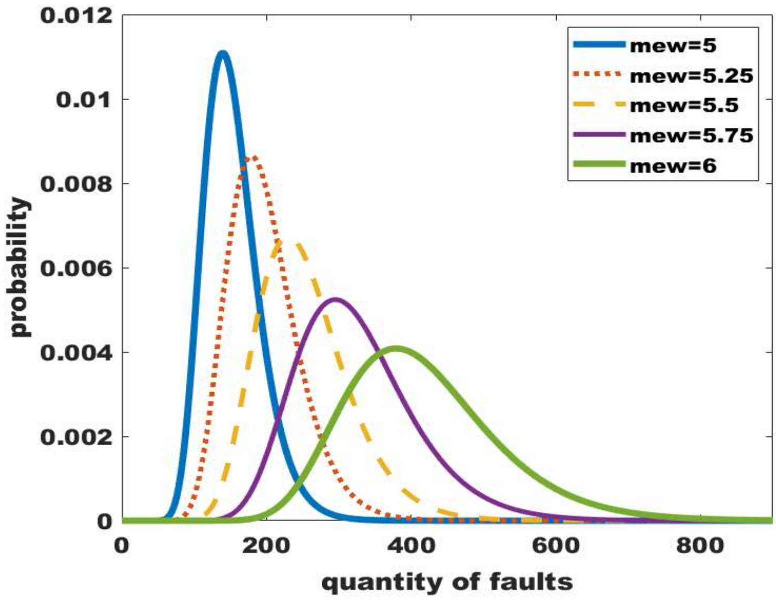

FIGURE 3. PDF(X) for σ =0.25, different μ

It is evident from Figure 3 that the quantity of faults reported in the literature (Flyvbjerg et al., 2003) [weather it is mean or mode of the sample] may be generated by different combinations of μ, σ. On Figure 15, a Log-normal PDF (μ=4.9, σ=1.7) was generated for the entire database.
μ and σ are functions of time [FIGURE 17].

3.2. Power function

The quantity of faults of the Log-normal variable is exponentially related to z [Equation 6]:
$x = e^{\mu+z*\sigma} = e^{\mu} * e^{z*\sigma} \sim e^{z*\sigma}$,
z has a normal distribution N (μ, σ):

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

thus:

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

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

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

The probability distribution [Equation 10] of the magnitude of faults is a power function.
(Newman, 2005) reports the work of (Miller, 1957), where the frequency of words is divided between letters.

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

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

We found that calculating “q” as a post-factum project mean, yields good predictions for construction projects, where “m” represents activities. Figure 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 $\frac{\sum x}{N} = 1 - q = 0.52$. This graph produces a good estimate [Figure 18.3, Figure 19.3]. “b” was calculated from Equation 12. “a” was calculated by integrating Equation 10.

Fun1

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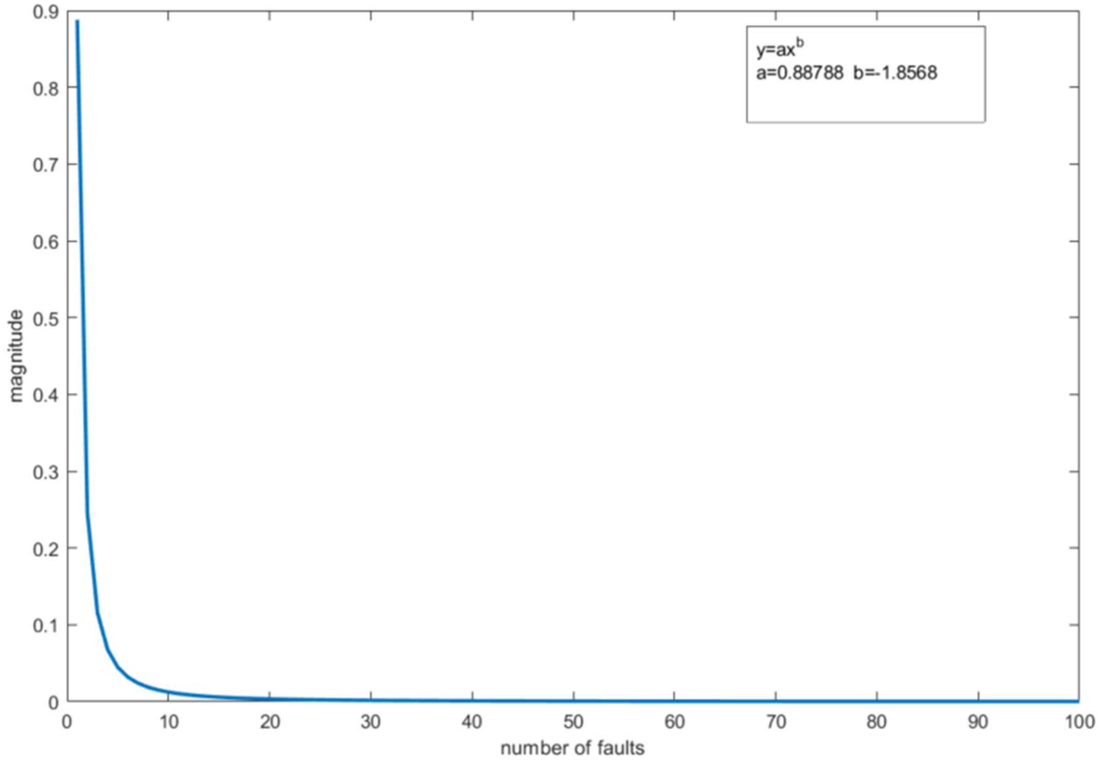

FIGURE 4. Power function generated using Equations (10), (12), Fun (1) for m=50, $\frac{X}{N}$=0.52, a=0.89, b=1.86

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 in one of a few projects. a>1 implies that the cost of a single fault may be greater than the cost of the entire project. a=a(X_{min}) [Fun1].
It is useful to present the function on log-log scale [Figure 5, Figure 19.3].

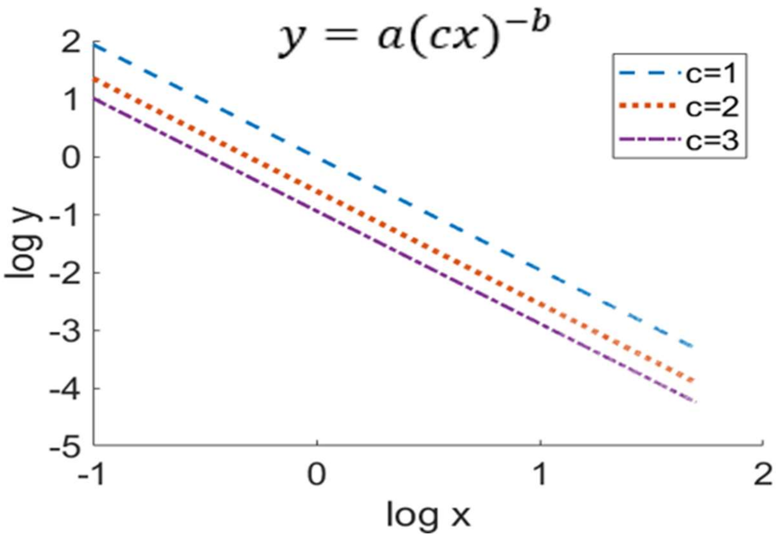

FIGURE 5. Log-Log Graph of power function

Figure 5 presents the function for scaled " x ". Where “y” stands for risk, “c” may represent different risk scales: cost, time, probability. Power function is scale-free. Multiplying the variable only changes the ordinate.
Figure 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 Figure 18], or different segments of the industry [b=b(m, q), Equation 12].

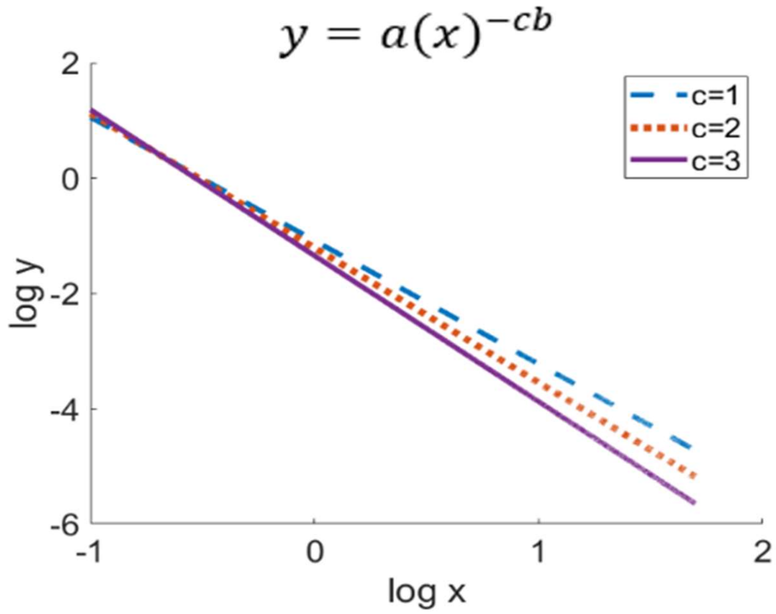

FIGURE 6. Log-Log Graph of scaled power values, b=1.946

Equation 12 may be used to depict the relation between “b” and q [Figure 7].

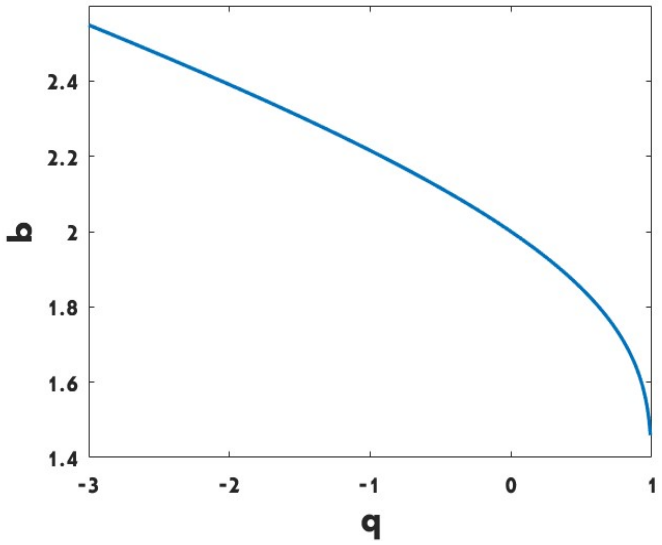

FIGURE 7. Power shift as a function of “q”

A project of N=150 weeks and a total of 300 to 600 faults, presented in the literature, yields $q \geq -3$ b<3. For q<0, there is a certainty (1-q>1) of faults on every $n \in N$. [q=q(m), table 2 q=q(morphology) Figure 10, q=q(t) Figure 9].
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 Figure 18).
According to (Albert & Barabasi, 2001), for 2<b<3 finite sub-graphs are formed. In the presence of randomness, the spatial overlap between subsequent avalanches becomes insignificant, and ultimately a critical state is not reached. These constitute a negative correlation between quality and risk.
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 [small faults as defined on 3.3].
A move from high fault probability projects to lower probability projects is a move to the right on the "b" curve of Figure 7, and a move between the curves of Figure 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).

3.3. 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".
These are DSP control operators [portrayed on Table 1]:
\> pass ["Ok"],
\>> back a step= one FB loop ["Reject"],
\>>> back two steps= two FB loop ["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: for the info-system, change orders are Rework.
A unit signal is represented here by the Kronecker delta δ[n] =1.
A Reject initiates one **F**eed-**B**ack loop [1FB].
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.
A Rework initiates a double **F**eed-**B**ack loop [**2FB**].
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 response 1,1,2,3,5,8,13, so that the signal is magnified (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 section **Error! Reference source not found.**] determines the magnitude of the faults (Tinós & Yang, 2007). The control signal is scaled by the power function. The PDF determines the recurrence of the signal. The signal passes through the control filters, ultimately feeds 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]. The systems are injectively determined by it. The outcome y[n] of a specific fault signal vector $x[n]$ $, n \in N$, N=the discrete time set, is the convolution (denoted by "$*$") of the impulse response h[n], and the fault vector signal $x[n]$: For an LTI

$$y[n] = x[n] * h[n] = \sum_{k=0}^{N-1} h[k]\, x[n-k] \qquad (13)$$

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

$$x[n] = \sum_{k \in z} \delta[n - kN] \qquad (15)$$

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:

$$\mathbf{X}(\omega) = \frac{2\pi}{N} \sum_{k \in z} \delta[\omega - \frac{2\pi}{N} k] \qquad (16)$$

A specific phase ($\frac{2\pi}{N} k$) matches a specific activity (k).
The Z transform of x(n) is:

$$\mathbf{X}[z] = \sum_{n=-\infty}^{+\infty} x[n]\mathbf{z}^{-n} \qquad (17)$$

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

$$y[n] = \sum_{k=-\infty}^{+\infty} h[k]\, x[n-k] = \mathbf{z}^n \sum_{k=-\infty}^{+\infty} h[k]\, \mathbf{z}^{-k} \qquad (18)$$

$$H[\mathbf{z}] \equiv \sum_{k=-\infty}^{+\infty} \mathrm{h[k]}\mathbf{z}^{-\mathrm{k}} \qquad (19)$$

$$y[n] = H[\mathbf{z}] * \mathbf{z}^n = \lambda\, \mathbf{z}^n \qquad (20)$$

H[**z**] is the eigenvalue of $\mathbf{z}^n$.
H[**z**] is called the Frequency Response.
Any signal can be synthesized from eigenvectors

$$x[n] = \sum_{k=-\infty}^{+\infty} \mathbf{X}[k]\mathbf{z}^n \qquad (21)$$

$$y[n] = \sum_{k=-\infty}^{+\infty} H_k[\mathbf{z}]\, \mathbf{X}[k]\, \mathbf{z}^n \qquad (22)$$

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

$$for\ n = k\ , \quad \mathbf{z}^{n-k} = \delta[n-k]\ \therefore \qquad (23)$$

Therefore $\delta[n - N]$ are eigenvectors of all LTI.
The difference equation for the 1FB-loop is:

$$y[n] - y[n-1] = x \qquad (24)$$

Z transform on (24) yields:

$$(1-\mathbf{z}^{-1}) * Y(\mathbf{z}) = X(\mathbf{z}) \quad (25)$$

$$H[\mathbf{z}] = \frac{Y[\mathbf{z}]}{\mathbf{X}[\mathbf{z}]} = \frac{1}{1-\mathbf{z}^{-1}} \quad (26)$$

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)
Rework double feedback loop	y[n]=x[n]+αy[n-1]+βy[n-2] (27)
Reject transfer function	$H(\mathrm{z}) = \frac{1}{1-\mathbf{z}^{-1}}$ (26)
Rework transfer function	$H(z) = \frac{1}{1-\mathbf{z}^{-1}-\mathbf{z}^{-2}}$ (28)

TABLE 1. The DSP control operators.

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

$$\delta[n-N] * h[n] = h[n-N] \quad (29)$$

The phase shift is

$$\varphi = arg\ \mathrm{H(s)} \quad (30)$$

The signal, a linear combinate of the "k" activities, has one frequency/period [Equation 16]. The outgoing signal has the same period, unaltered by the LTI system [Equation 18].

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).

3.4. Time

Time effects the system through various mechanisms:

1. The length of time itself is an entropic cause for errors, trough fatigue, carelessness, time pressure, outdated design, and inadequate code assimilation, rendering the barriers ineffective (Love et al., 2012).
2. Via repetition. A repetitive process with a non-diminishing fault additive and no correction bifurcates rapidly. [Appendix A.1]
3. Morphology and time generate trajectories of multiplication and propagation of faults on the spatio-temporal map [Figure 20].
4. By changing the morphology of the info system [Figure 14].
5. By changing the morphology of the system [m=m(t)].
6. Time shift causes a phase shift, and vice versa (Trigo, 2019):

   $$DTFT\ \{\textstyle\sum_{k\in Z} \delta[n-kN]\} = \omega_0 \textstyle\sum_{k\in Z} \delta(\omega-\omega_0 k) \quad (32)$$

   Phase represents activity; therefore, the project is out of the designated activity; this causes time delays and cost inflation.

   A "corrective" action of recuperating lost time by scaling down the duration of activities ("crashing time") adds to the previous outcome:

   a) Information loss.

   b) A time delay of an incoming fault is scaled up by the speed-up (scaling) factor:

   For $y[n] = x[\alpha n], \alpha > 1$, a delay in time of τ:

$$y[n-\tau] = x[\alpha n - \alpha\tau] \quad (33)$$

3.5. 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 [Figure 17.2- the IC threshold]. There is little redundancy 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 the system self-organizes to be stable at it. The IC self-adjusts to be "correct" (Heyligen, 2002). Past this threshold the system avalanches [Figure 17, project 22 avalanches after 5 iterations, thus the outcome exactly corresponds to table 2].

The factors that constitute the actual information load on the info-system and the causes of information overload:

3.5.1. The convolution of fault vector and the info-system causes stacking [Figure 8].

3.5.2. The info systems are complex nets [Figure 13, "small world" systems characterized by preferential attachment, scale free nets, and power function rank]. The info system nets' morphology is modified by time and faults [Figure 14]. T

3.5.3. he effects of liability and prestige sever triadic connections and form bridges of delayed and biased connectivity [Figure 14].

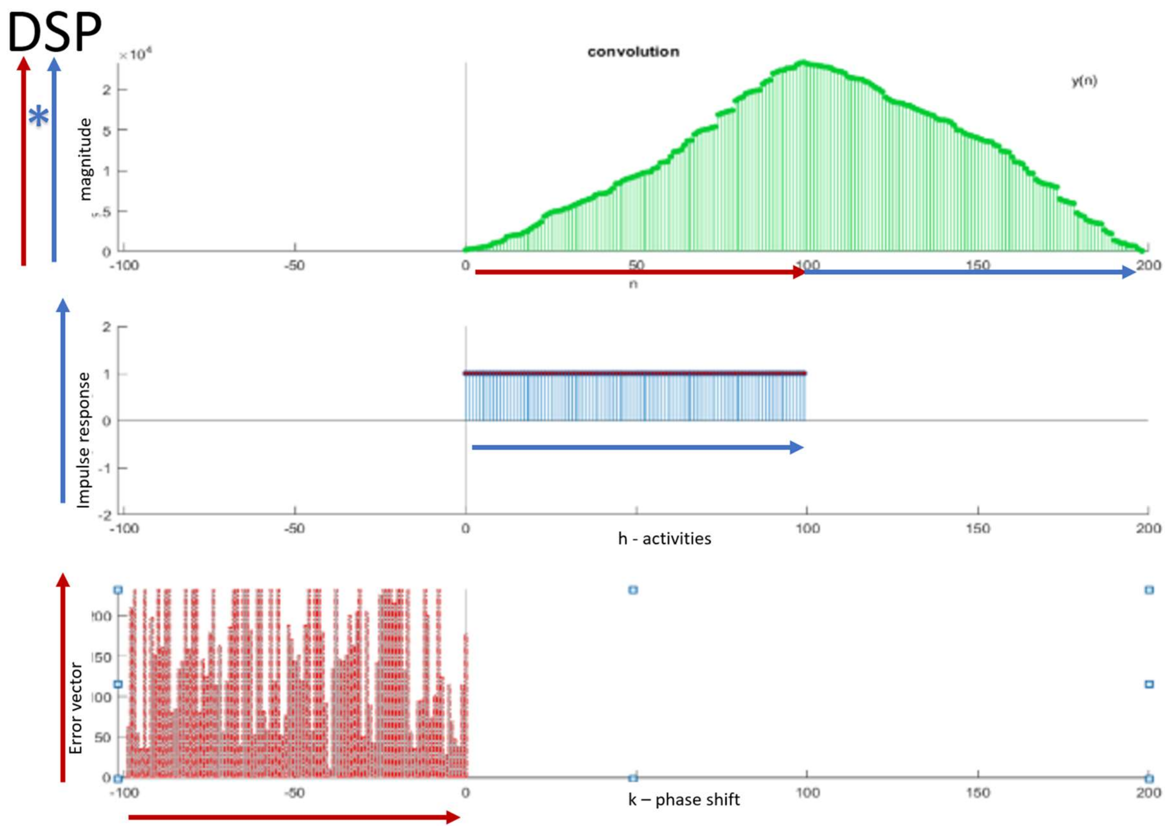

FIGURE 8. Information convolution in info-system. In red the entering Redo orders [Equation 16], in blue the system the Frequency Response [Equation 19], in green the convolution [Equation 22].

3.6. Barriers – Preventive Means

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 product of information. Negligence and incompliance enable the penetration of the barriers. Past the barriers, events are met by the QC. At that point, they are denominated **Faults**.

3.7. 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. Corrective means for faults are behavioural: An energetic, rapid response with open mindedness (Hare, 2009) and a trouble-shooting culture (Müller & Jugdev, 2012) are the means to success (Pinto & Slevin, 1987). In many instances these are not applied.
For this gap we suggest a system of data analysis b,ased on DSP, descriptive statistics and PID management that can give real-time alerts and initiate 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.

4. DISCUSSION

The Via Trita constitutes the barriers that shield projects and infrastructure from aleatoric risk [3.6]. Any divergence from the Via Trita, whatever small perturbation [Figure 9], may cause immeasurable disasters [Figure 20]. That is a cause of the conservativeness of the construction business.
The power function governs the magnitude of faults. The power factor is responsible for the segmentation of the market [Figure 6, Figure 7, Figure 19.4], to the stupendous number of small effect faults [Figure 19.2], and to the high magnitude faults of low probability recurrence [log x<0, Figure 19.3]. The inverse relation of quality and risk [Figure 7] is enabling the general neglect of quality. Moreover, the construction site systems adjust to poor quality. Systems develop robustness, manifested in high tolerance to defects [Figure 17], defect insurance (Ilozor et al., 2004), and compensation and litigation procedures. Contractors have devised a "start-fail-flee" strategy that is their recourse to high magnitude failures (Abdul-Aziz, 2002). A high "a" multiplier of the power function is a product of low x [Figure 19.3].
The power function mathematics suggests that the distance to the abscise [the "y" ordinate] diminishes more rapidly than the distance to the ordinate. White noise effect [Figure 18.4] consistently emerges in the data, indicates that the actual function is of the form: $y=a*x^{-b}+c$.
The scale-free trait is the reason why uneven dataset, biased and partial [Appendix B], still produces reliable results. Figure 20 tracs a 3D cause-spatio-temporal trajectory of faults. This is a means for pinpointing and projecting the progression of faults to avalanche in real time for prevention and mitigation and in post-factum analysis, - for claims.
Practical knowing dictates the addition of α, $\alpha \leq 1$ to the difference Equation 24 to represent a diminishing signal. $\beta \leq 1$ in the difference Equation 27 goes a long way in explaining Figure 17 and $\alpha, \beta \leq 1$ Figure 20. Negative feedback loops act to return the Info-system to its balance, neglecting the fact that the actual fault avalanches through the physical system, thus, detaching the info-system from reality.
Small world nets cause imported risk [Figure 17]. Scale invariance [Figure 13] enables the paradigm of autonomous agents being responsible for their scale invariant role and laissez-aller management. These facilitates the free exchange of personnel, equipment and sub-contractor between companies and projects, making the whole industry interconnected (Gidado & Wood, 2008). The morphology of the net and especially the formation of clusters and bridges [Figure 14], elucidates one mechanism of information overload generation, and the disproportional influence of the designers. BIM amplifies the effects of centrality and convolution by the enlargement of the information traffic volume and speed. This explains the findings of (Jupp, 2017) that BIM aggravated design info overload caused problems.

The information system causes the different trajectories of faults and defects, and the difference between big companies, who 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. Figure 17 is a manifestation of double IC, one for faults and another for defects, the first is in the site info-system and the second is site personnel [(Newman & Sneppen, 1996) for b>2]. On Figure 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 to avalanche [Figure 17]. Avalanche changes the morphology causing phase transition [Figure 18] and after-shocks (Newman & Sneppen, 1996).
QC performance is studied on Figure 19. Figure 19.1 seems to present a black swan phenomenon. A small project that overtakes the entire accumulated effects. On a closer look -Figure 19.2 shows that QC performance exhibits a clear disparity: some projects are neglected altogether, while QC on project 19 is overzealous.

The literature suggests that design is the paramount fountain of faults, and specifically the large magnitude ones [(Rosenfeld, 2013), Figure 17]. Design is not only a cluster in the complex information system [Figure 13], it is the first cluster, it forms bridges, and it has high centrality [Figure 14]. Designers are participating in multiple projects at any time, causing systems to be interconnected, to import risk and rank, causing systemic information faults and psychological effects of time [section 3.4]. Unlike other faults, that are processed by QC, the products of design enter directly into the information system to be convoluted there [Figure 8]. Propagation and multiplication of design faults simulated on Figure 10, should be corrected for preferential attachment morphology that aggravates the effects. Combined with laxity of control, and the latency of design faults, propagation and multiplication cause a Figure 9 type avalanche [the butterfly effect i.e. small perturbations that cause unlimited effects]. Design processes are recursive, aggravating design faults amplification and propagation through the different design disciplines and throughout the project activities. Design generates physical systems where errors are embedded in the physical morphology. Most design errors are latent in the design, manifested only at the stage 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 info-system before commencement of construction, causing friction, extra costs, more time effects, and litigation. Some are detected while executing, causing avalanche, risk allocation power struggle, and more cost and time overruns. Some errors propagate to the facility operation stages.

Time is a factor in all causing factors, acting as an accelerator. Time and morphology are interchangeable [Equation 32, Figure 5]. Change-orders are identical to faults [section 3.3], they change morphology and activities. Claims reimbursement should compensate for all implications incurred in and generated by the info-system, and for the risk instigated by the added information load. Prevailing compensations cover direct costs and overhead, not accounting for the fact that change-orders change the activities [Equation 32], causing time and cost implications, and sometimes even drive activities out of sync, causing clashes and stuttering halts of work and constrained resources
Having deciphered the modus operandi of complex mechanic systems, the like of stormwater systems, PID DSP control is straight forward. It is a recurring phenomenon that the gauge produces an Integral signal. In physical systems, water level [and 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 are of scientific interest. PID gives indication of the past [the Integral-Figure 17] present [Proportional-Figure 9] and future [Derivative-Figure 11] thus enabling decision support and action generation [section 3.7]. These means transform QC from a system that reports faults to a quality management system.

5. CONCLUSION

To the theoretical and practical gap in the understanding and management of risk in complex systems, **ToF** provides a theoretical framework and tools for analysis and management, enables the development of automated response for infrastructure and the directing of prevention and mitigation actions for projects. A database addressed the gap in data. 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, complex nets, and the statistics of chaos to model, explain and predict behavior of complex systems is a novelty. ToF has been applied to various systems with good effects, showcasing the potential contribution for operation, and for prevention and mitigation.
Logical agent-based AI is a promising future development. Inferences accumulated by the system may be added to its Knowledge Base and propositional logic may be modeled on the acquired understanding of the system's modus operandi.
The effects of complex nets and the limited IC threshold [Figure 17], the power function effects [3.2] and the emergent traits of risk neglect, the skyrocketing risk [Figure 9] and correlated risk [Figure 17], the avalanche and after-shock effects [Figure 18 and Figure 14], are all an urgent call for the introduction of contractual fail-safe mechanisms that would evoke corrective actions directed by means proposed here.

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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

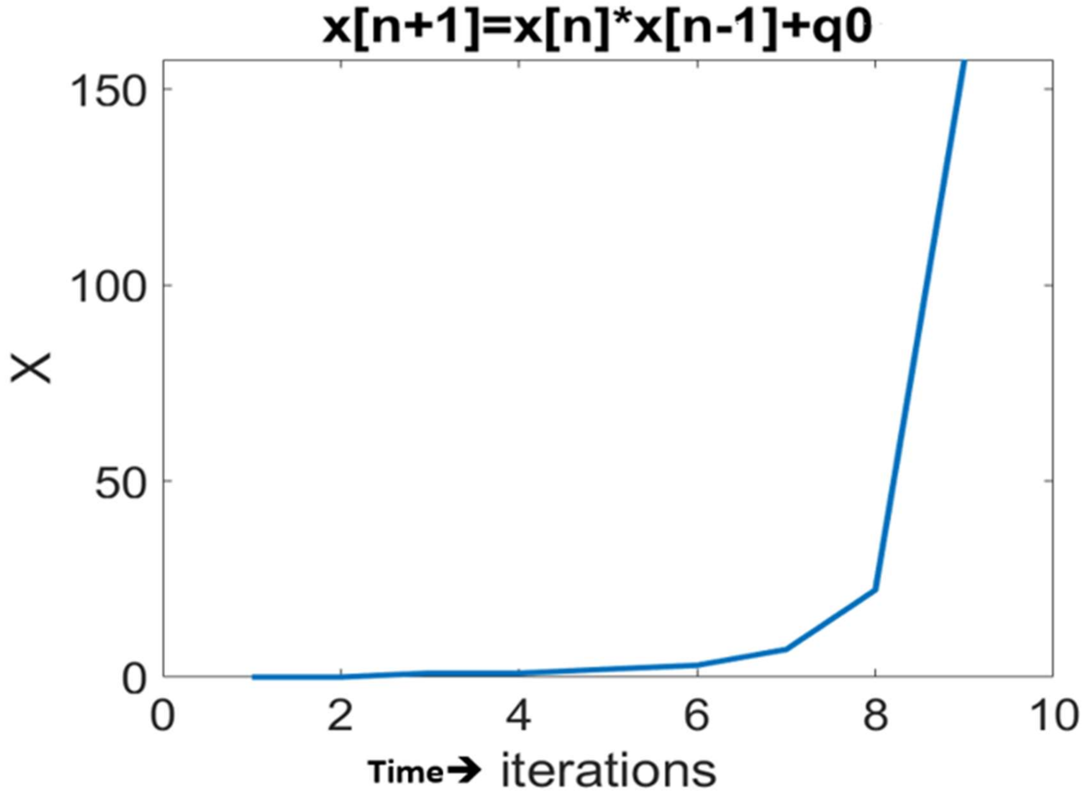

FIGURE 9. Time affects via repetitions [“bifurcation”]. q0=0.002

A2. Cellular automata

a bounded random walk.

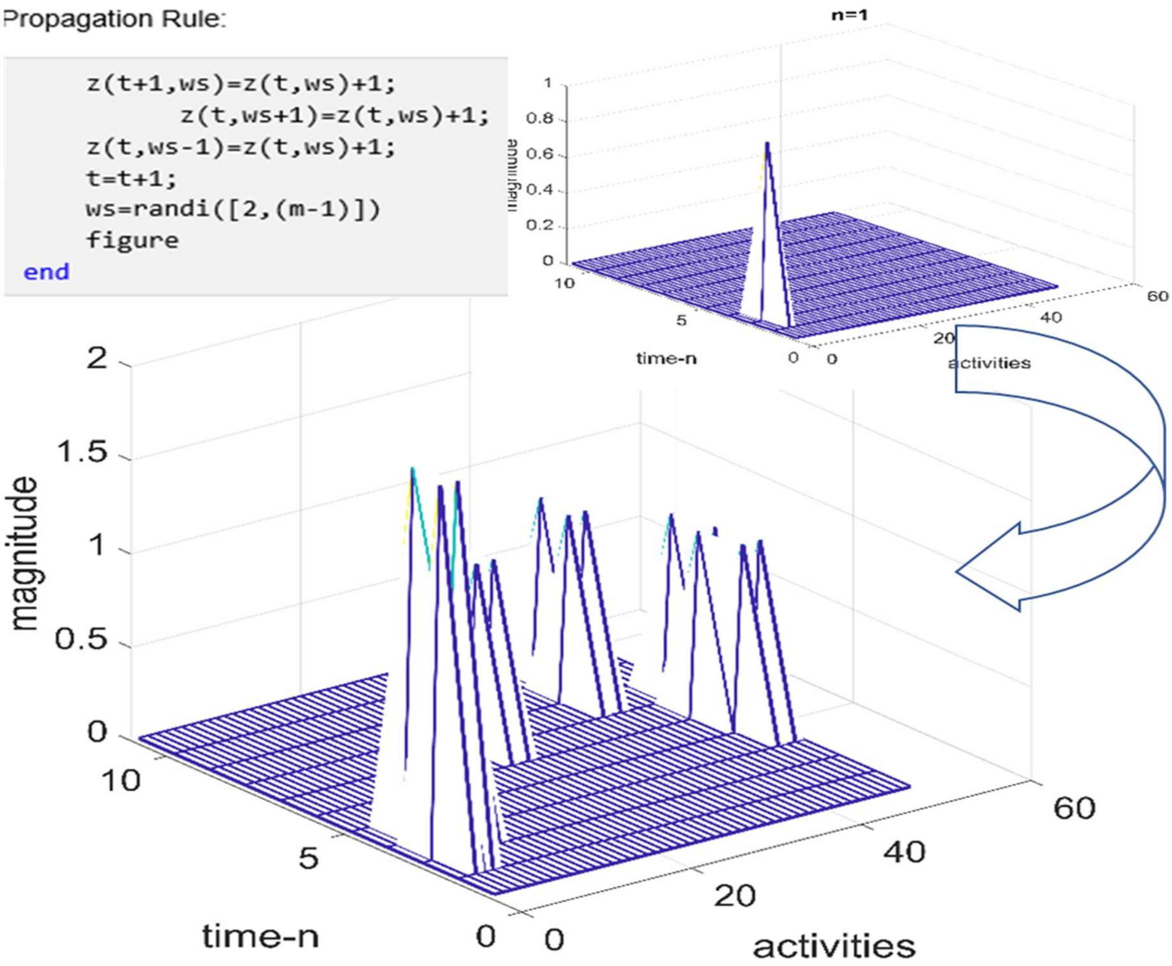

FIGURE 10. Cellular automata iteration 7

A3. Numerical experiment

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

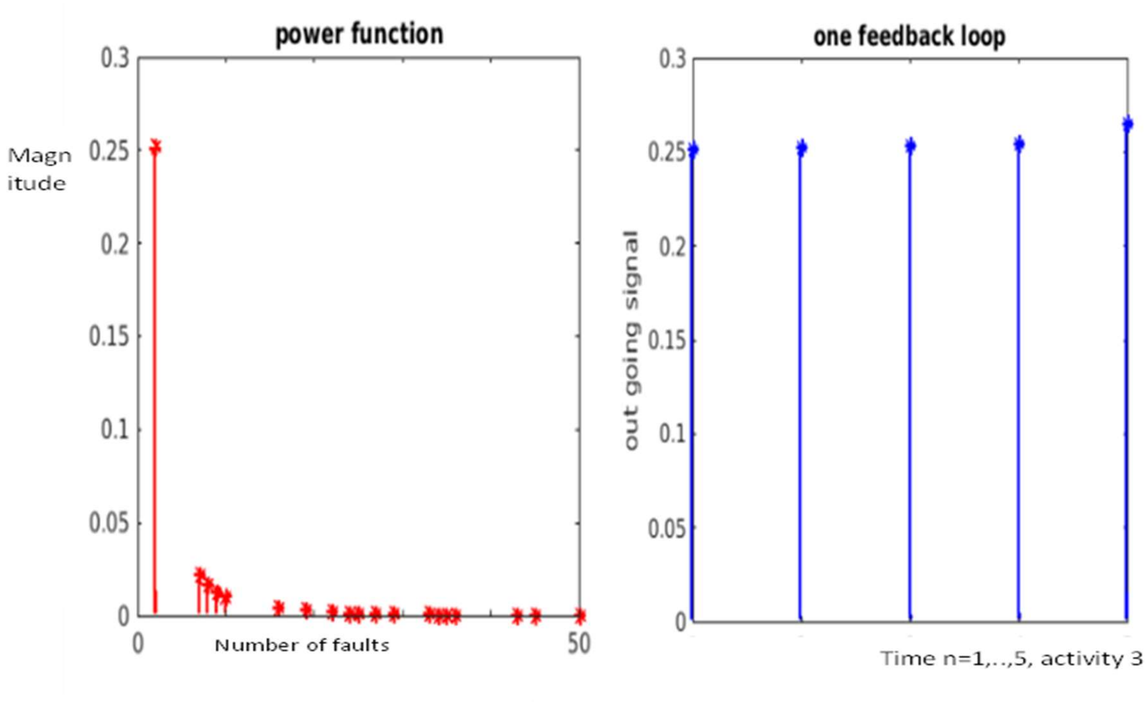

FIGURE 11. 1FB loop amplification

TABLE 2. 2FB loops random iterations:

	1	2
	0.001	
2	0.007	
3	0.014	
4	0.0233	0.
5	0.0431	0.

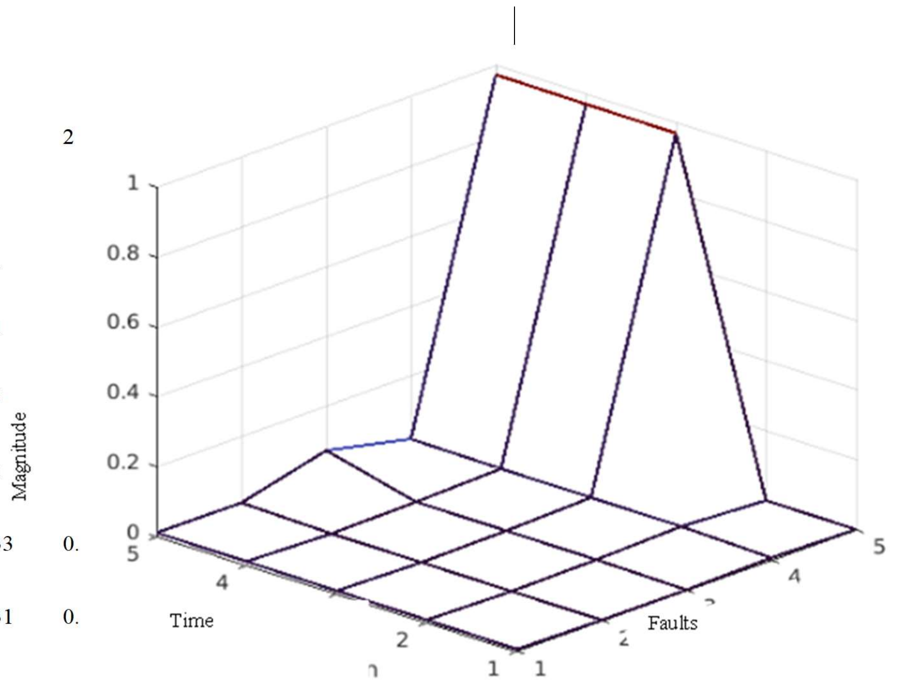

FIGURE 12. 1FB loop amplification of extreme event, the entering power function (left) and the amplification (right).

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 Figure 14 curve fitting yielded a=-1.523 [R^2=0.9365].

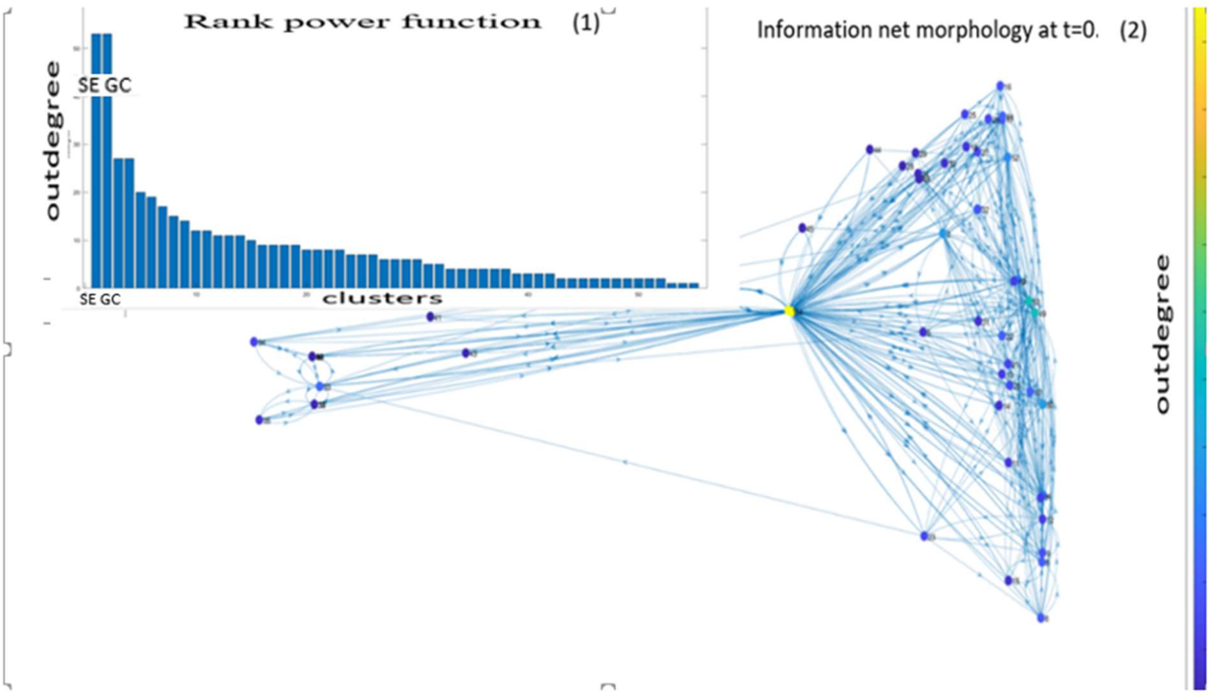

FIGURE 13. Information net morphology at t=0. Nodes represent autonomous agents [such as designers and sub-contractors]. Nodes have a power rank [13.1], therefore, the net is complex.

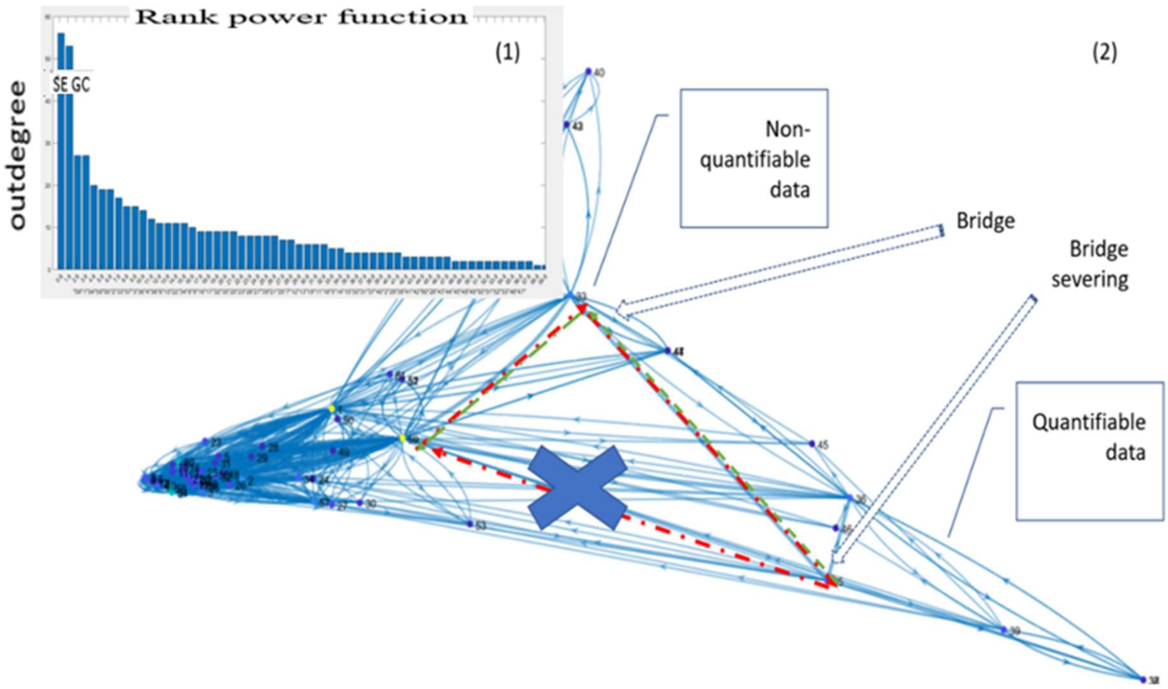

FIGURE 14. Information morphology after a redo order originated in a design error. Rank is changed [14.1], the centrality of site system emerges, the weight of edges is changed, triadic connections are severed, and bridges formed.

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 [Figure 15], power functions were machine fitted to each project. The resulting functions were compared [within the limitations of the data] to Figure 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 [Figure 17].

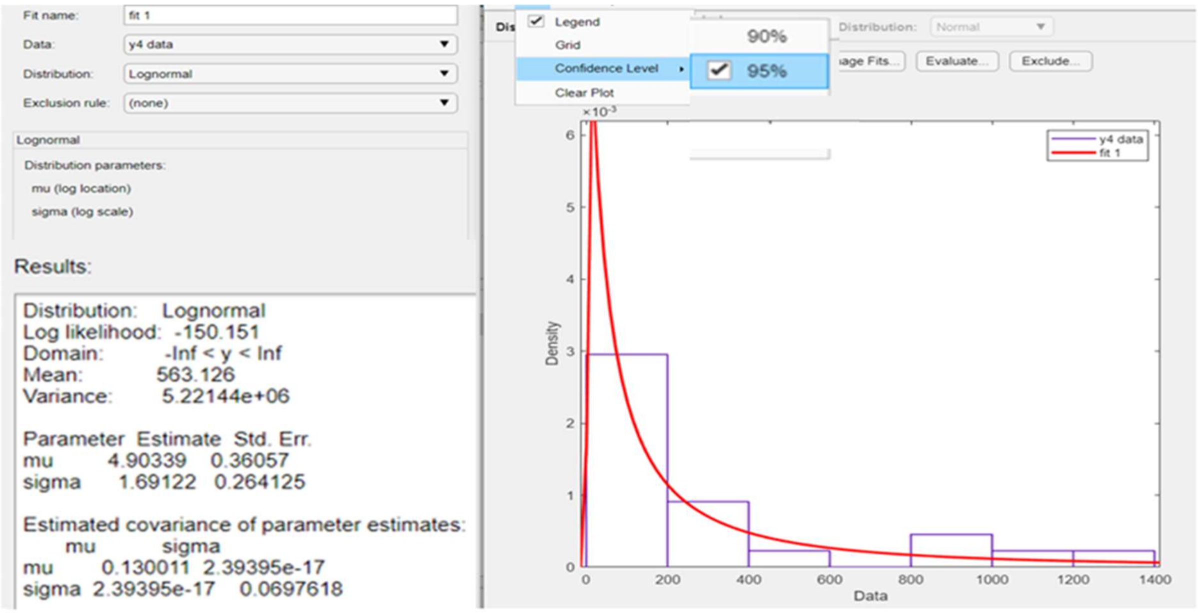

FIGURE 15. PDF for 27 projects [95%confidence level], bins=18

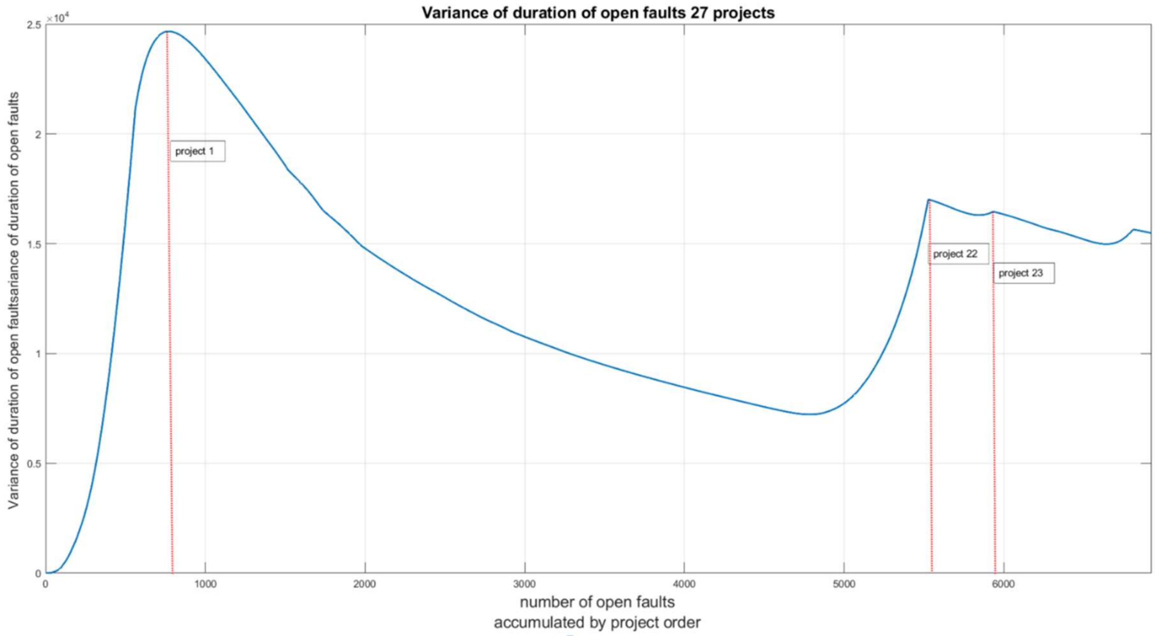

FIGURE 16. Cumulative variance of 27 projects, accumulated by order of projects. The magnitude of avalanche goes to infinity, thus the mean and stdv.

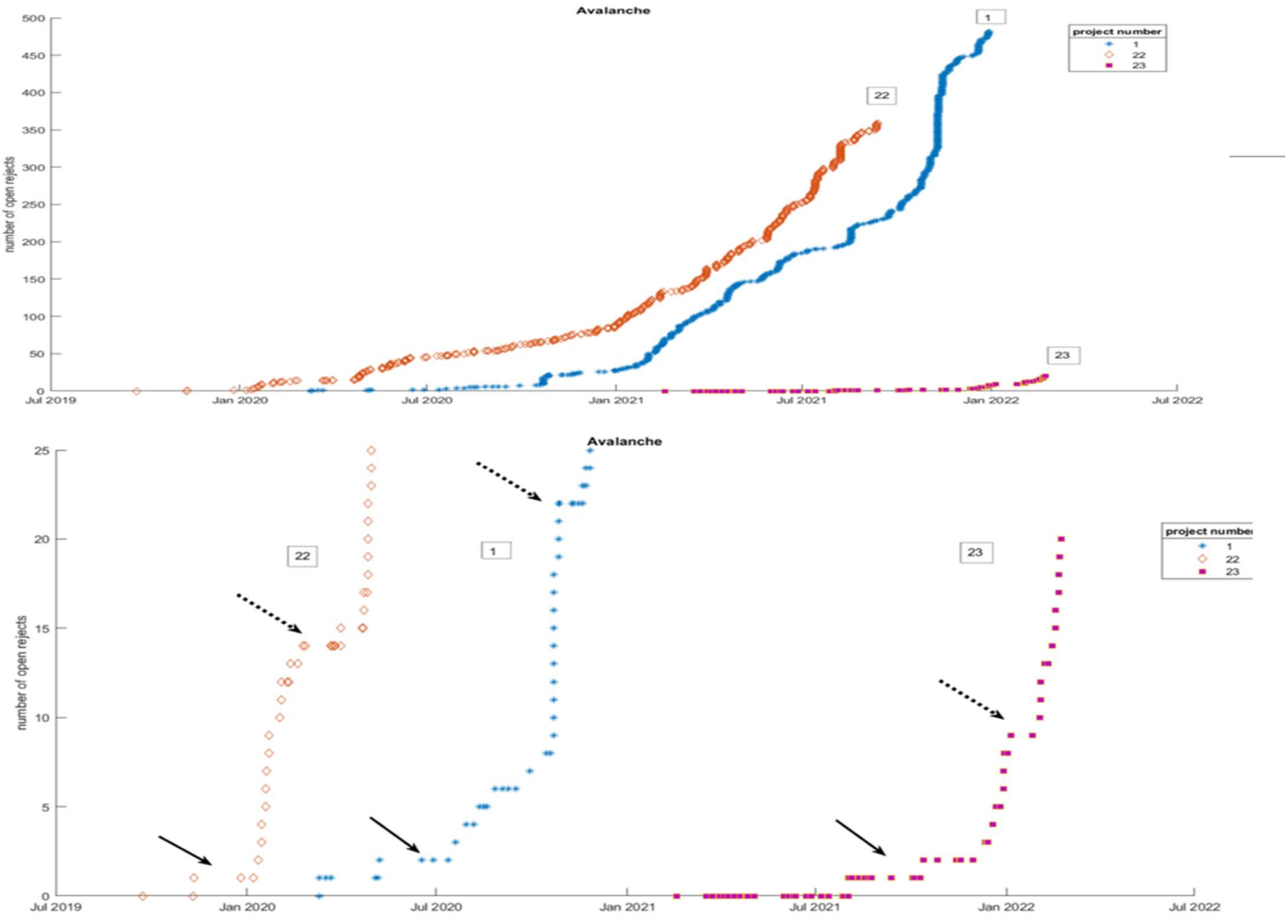

FIGURE 17. The integral of open rejects for three "light" train projects: Project "1"- civil engineering works, Project "22"- systems and project "23"– control. The bottom blown out part – the IC [the bifurcation point, marked by arrows] and second IC [marked by dashed arrows].
As faults started on the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

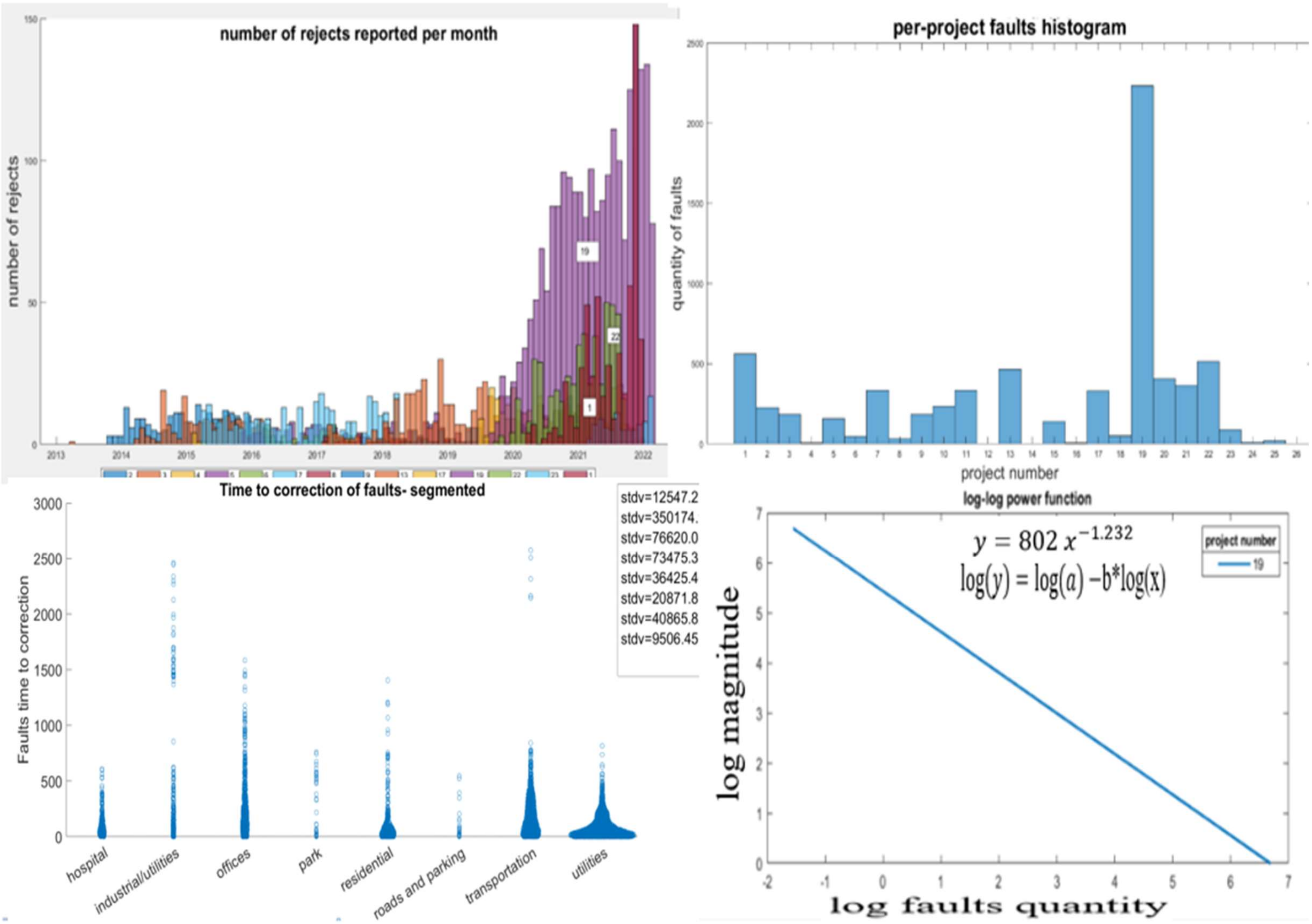

FIGURE 18. clockwise: 18.1 superposed graphs of number of faults, 18.2 the total number of faults per project, 18.3 log-log power function of project 19 showing an avalanche of defects, 18.4 segmented time to correction of faults and their stdv.

Figure 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 Figure 16 are not reflected in Figure 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 [Figure 20].

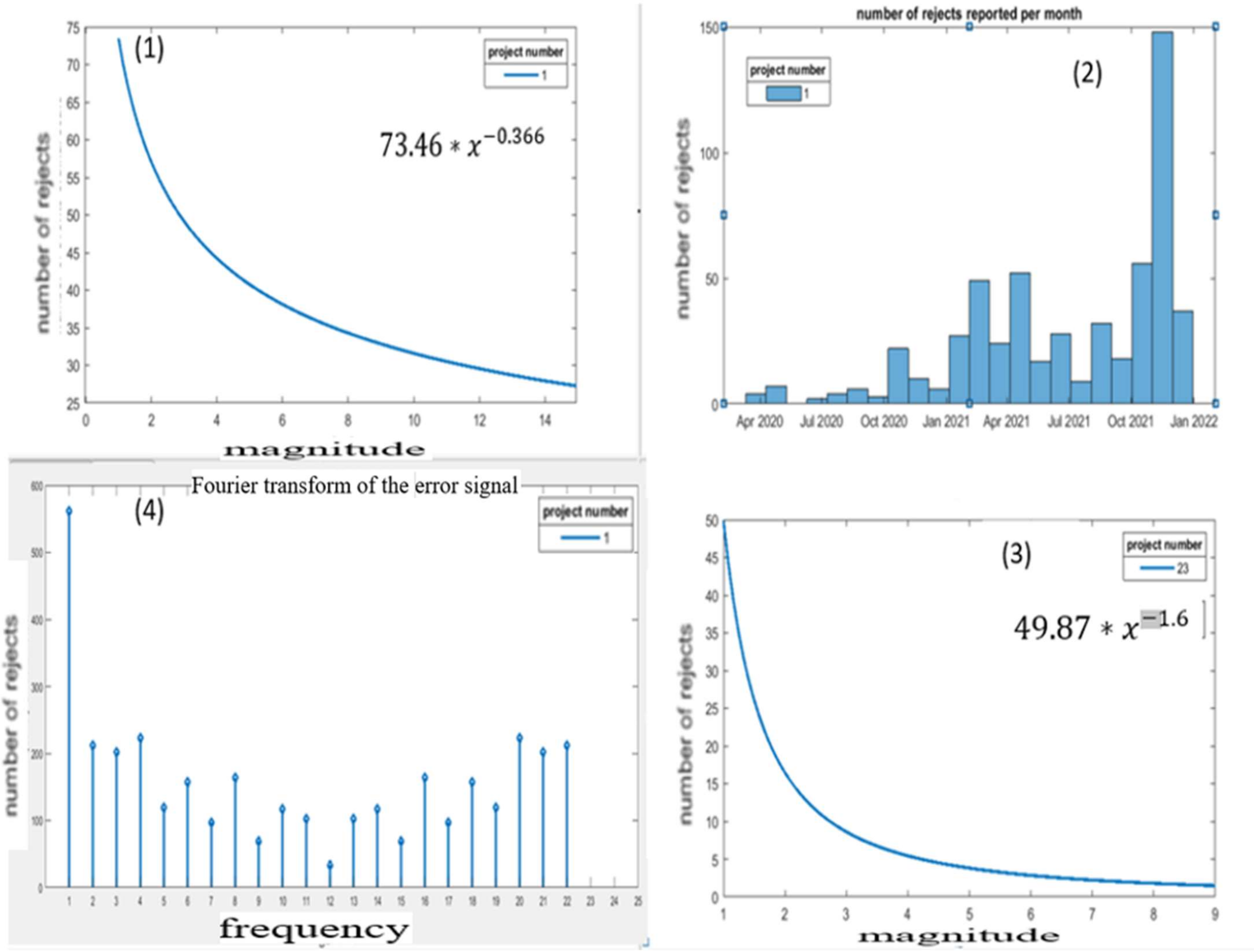

FIGURE 19. Power f unction for the avalanched projects [19.1] where "a" factors the magnitude to the relevant scale [compare to Figure 5, for "a" =ac^{-b}]. The histogram [19.2] pinpoints the time of avalanche, the Fourier transform of the error signal [19.4] shows white noise traits of frequency. The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

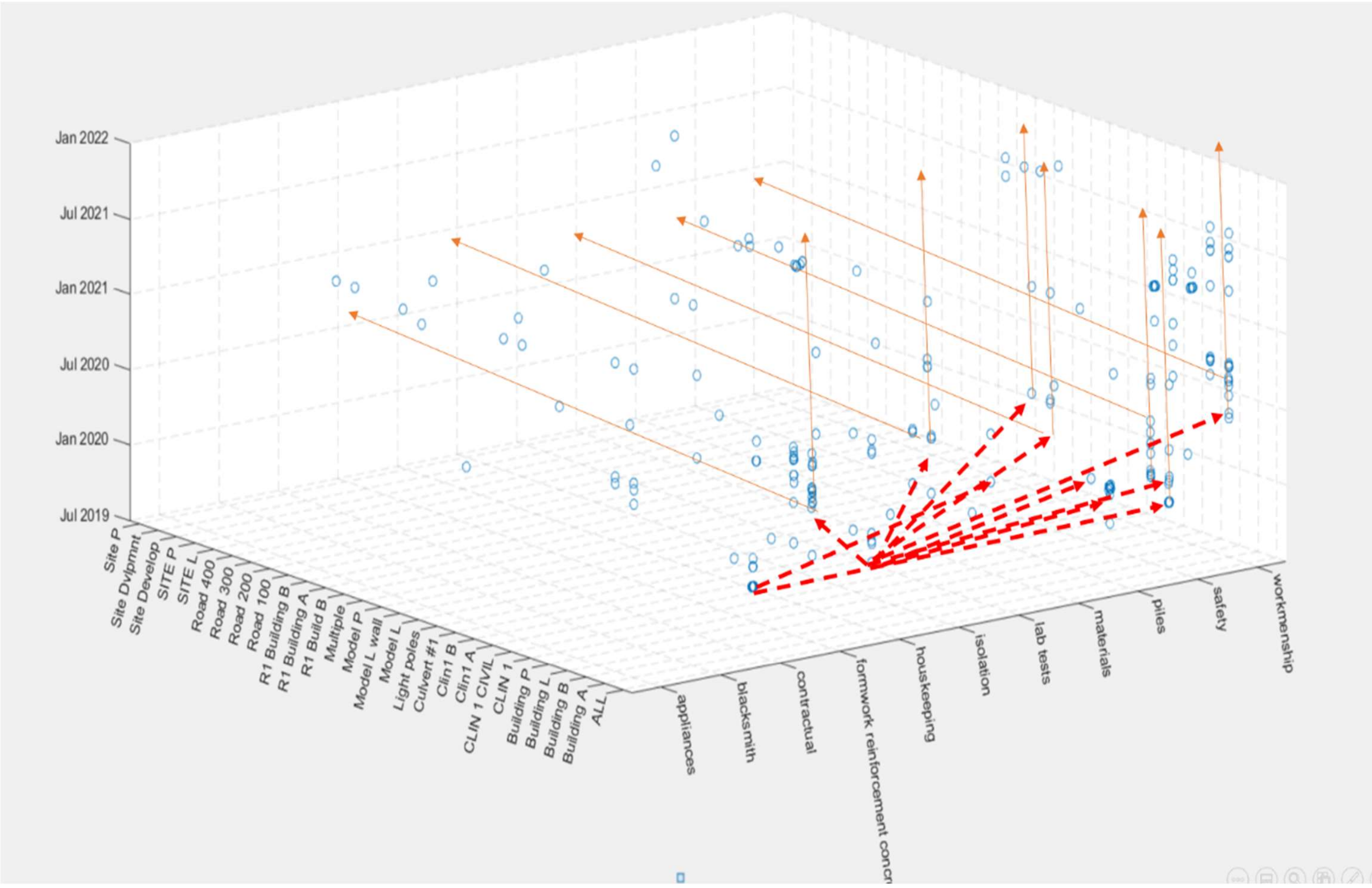

FIGURE 20. A storage facility 3D scatter plot- causal spatio-temporal with a fault trajectory [added manually using the deficiency list natural language description]

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. https://doi.org/10.7202/1072334ar

Heron, J., & Reason, P. (1997). A participatory inquiry paradigm. *Qualitative Inquiry, 3*(3), 274-294. https://doi.org/10.1177/107780049700300302.

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

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. https://doi.org/10.1016/j.proeng.2017.04.178

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. https://doi.org/10.1061/ASCECF.1943-5509.0000116.

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. https://doi.org/10.2307/1419346

Mills, A., Love, P. E., & Williams, P. (2009). Defect Costs in Residential Construction. *Journal of Construction Engineering and Management, 135*(1), 12-16. https://doi.org/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, Ubiraci Espinelli Lemes, & 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