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A COMPLEXITY MEASURE FOR CONCURRENT ENGINEERING PROJECTS BASED ON THE DSM

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Keywords: complexity, concurrent engineering, work transformation matrix, performance fluctuations

1 INTRODUCTION

The successful management of New Product Development (NPD) projects is an important source of gaining competitive advantages. To shorten the development time, lower the development-production costs and improve quality, NPD projects are often subject to Concurrent Engineering (CE). CE is a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. Due to their inherent complexity, CE projects often face severe problems, such as budget and deadline overruns, missed specification and, therefore, customer and management frustration. Many CE projects end up failed and abandoned and therefore there is a certain need for innovative models and methods for coping with complexity. The goal of this paper is to introduce a novel complexity measure for CE projects which is theoretically underpinned by a sound complexity theory of basic research, and uses a rigorous model of project dynamics to assign complexity values. Our approach can be phrased as "holistic" or "non-reductionistic" because it is able to cope with a large number of individuals in CE teams who make at least partially autonomous decisions on product components but also strongly interact in their impact on project performance.

2 DYNAMICS OF CONCURRENT ENGINEERING PROJECTS

In order to derive the novel complexity measure in a simple explicit form in section 3 a model of project dynamics is introduced. Therefore, the fundamental work of Smith and Eppinger [3] on deterministic project dynamics is considered and extended through the concept of multivariate random variables to model performance fluctuations. According to Smith and Eppinger, the dynamics of a CE project with p fully concurrent tasks can be modelled by a first order linear difference equation: $\mathbf{x}_t = \mathbf{A}_0 \cdot \mathbf{x}_{t-1}$, $t \geq 1$. The matrix $\mathbf{A}_0$ is the $p \times p$ Work Transformation Matrix (WTM). The column state vector $\mathbf{x}_t$ represents the work remaining of all p tasks in time slice t. The WTM does not vary with time and the state equation is said to be autonomous. In this paper the improved WTM concept of Huberman and Wilkinson [2] is used. Hence, the entries a_{ii} ($i = 1 \ldots p$) in the main diagonal of the WTM account for different rates of progress on different tasks and can be considered as autonomous task processing rates when no interactions among tasks occur. This is in contrast to the original WTM model where the tasks are performed at the same rate. To be precise, a_{ii} indicates the part of work left incomplete after one time slice for task i and therefore must be a positive real number, which in well planned projects is smaller than 1. The off-diagonal entries a_{ij} ($i \neq j$) are arbitrary real numbers in the interval [-1;1] and have three different meanings: 1) a positive entry indicates that one unit of work on task j in time slice t causes a_{ij} units of rework on task i in time slice t+1; 2) a zero entry signifies that task j has no direct effect on task i; 3) a negative entry models that efforts on task j in time slice t accelerate the completion of task i in the next time slice. In the first time slice it is usually assumed that all p tasks are 100% undone and there is $\mathbf{x}_0 = [1\ 1\ \ldots\ 1]^T$. The WTM can be created for a particular CE project by assigning numerical values to the design structure matrix (DSM) of the product to be developed. For instance, Lukas et al. [3] developed a "rework matrix" for the development processes of a power-train control unit at Daimler AG. The fundamental weakness of the deterministic project model is to assume a perfect predictability of task processing and to ignore the significant amount of "noise" occurring in real CE projects (see [2]). This noise allows different interpretations. When looking inwards from outside of the project the noise reflects the capacity limits of the project manager and the participating engineers when processing large amounts product and process information, and can therefore be considered as an effect of ignorance. When looking outwards from inside of the project, the noise reflects nonpredictable exogenous fluctuations of the business environment, e.g., slightly changing customer requirements, a change in the priority of design objectives, unsteady maturity of involved technologies, etc. Hence, we believe that it is reasonable to model CE projects as an open system. In order to do so, an algebraically simple but conceptually important development of the deterministic model is given by the linear stochastic difference equation

$$X_t = \mathbf{A_0} \cdot X_{t-1} + S_t \qquad t \geq 1. \tag{1}$$

$\mathbf{A}_0$ is the WTM. The p components of the project state vector X_0 in time slice zero are typically not subject to random fluctuations. Instead, they are set to positive real numbers in order to represent the percentage of work remaining according to the initial project state. In spite of the deterministic project start, the regime in the following time slices is stochastic and a sequence of independent and identically distributed (iid) multivariate random variables S_t is added to the project state to model fluctuations. In real CE projects there are many stochastic influences acting on the work progress. Although we neither know their exact number nor their distribution, the multivariate central limit theorem tells us that, to a good approximation, a sum of iid random vectors can be represented by a normally distributed vector. In other words, if at each time instant the sum of many fluctuating influences acts on an CE project, the total effect at each time instant can be thought of as a Gaussian random vector. We assume that the noise has no systematic component influencing average project dynamics and the random vectors S_t follow the multivariate Gaussian distribution with zero means and a covariance matrix $\mathbf{\Sigma_S}$: $S_t \sim N(\mathbf{0},\mathbf{\Sigma_S})$, $t \geq 1$. The covariance matrix $\mathbf{\Sigma_S}$ is the natural generalization of the variance of a scalar-valued random variable to higher dimensions. The σ_{ii} entries in the main diagonal of $\mathbf{\Sigma_S}$ denote the variance of the fluctuations of task i. If σ_{ii} is large, task i is heavily perturbed. The stochastic project model defined in eq. (1) is asymptotically stable if and only if all eigenvalues λ_i of $\mathbf{A}_0$ have modulus less than one. If this is not the case, the project is divergent and the work remaining grows over all limits. If the project is asymptotically stable, the convergence rate of the work remaining is dominated by the largest eigenvalue $\lambda_{max} = \max(\{\lambda_i\}]$. λ_{max} is therefore called the dominant eigenvalue. The larger the dominant eigenvalue, the lower the mean convergence rate. The supplementing slides show traces for three basic project organizations with only two tasks. Furthermore, the fundamental effect of excited fluctuations due to task coupling is shown which can lead to a significant "design churn".

3 COMPLEXITY MEASUREMENT

Surprisingly, complexity theories of basic research have rarely been considered in the DSM community. A highly satisfactory complexity theory and an associated measure were developed by the theoretical physicist Grassberger [1]. His forecast complexity represents the amount of information required for optimal prediction of behaviour of a complex system. We believe that this approach is also reasonable in project management, because there is a limit on the accuracy of any prediction of a given project that is set by the characteristics of the project itself. For instance, there is a limited precision of measurement of work progress, maturity of technology, etc. Even the most experienced project manager cannot exceed this level of prediction accuracy. Suppose we had a maximally predictive project model, i.e., its predictions were at this limit of accuracy. Prediction is always a matter of mapping input to output. In our context the inputs are the traces of work remaining. However, in most projects not all aspects of the entire past are relevant. In the extreme case of "perfect" chaos, the project past is entirely irrelevant and the work progress is completely randomized from time slice to time slice. Conversely, in the case of a completely predictable and repetitive work process with period l, one only needs to know which of the l phases the work sequence is in to make perfect predictions. If we ask how much information about the past is relevant in these two cases, the answers are 0 and $\log(l)$, respectively. Hence, highly random and highly deterministic CE projects are of low complexity. More interesting cases arise if there are multiple interactions between tasks due to a coupled product design leading to extensive cooperation and communication of the engineers. In this case long-range informational interactions are generated and significantly higher complexity values must be assigned. Following these lines of thought we define an Effective Measure Complexity (*EMC*) of project dynamics. *EMC* represents the mutual information between the past and the future of a CE project and is a lower bound of the unknown forecast complexity. *EMC* can be estimated from either a project model (eq. 1), as we do in this paper, or from project data alone, without intervening models. Since it can quantify the degree of "informational structure" between the past and the future, it is an especially interesting measure for CE projects. The derivation of *EMC* on the basis of the project model from eq. 1 is mathematically involving and not given here. We only present the final result in eq. 2.

$$EMC = \frac{1}{2}\log_2\left(\frac{\det\left(\sum_{k=0}^{\infty}\mathbf{A_0}^k \cdot \mathbf{\Sigma_S} \cdot (\mathbf{A_0^{\mathrm{T}}})^k\right)}{\det\left(\mathbf{\Sigma_S}\right)}\right) \tag{2}$$

The novel complexity measure from eq. 2 has six favourable properties: 1) *EMC* is small for projects with uncoupled tasks and assigns larger complexity values to intuitively more complex projects with the same dominant eigenvalue λ_{max} (determining the mean convergence rate of work remaining), but stronger task couplings. 2) The measure indicates the same bounds of project stability as the classic eigenvalue analysis: if the dominant eigenvalue λ_{max} of the WTM $\mathbf{A}_0$ has modulus less than 1 the infinite sum in eq. (2) converges and finite complexity values are assigned. On the other hand, if λ_{max} has modulus greater than 1 the infinite sum diverges and infinite complexity values indicate a diverging project. 3) The measure tends to assign larger complexity values to projects with more tasks if the task couplings are similar, and therefore is sensitive to the cardinality of the project. Alternatively, one can divide *EMC* by the dimension p of the state space and compare the complexity of projects with different sizes. 4) The measure is able to cope with fluctuations and performance variability in project dynamics and is able to assess emergent design churn effects. (5) The measure is independent of the basis in which the state vectors of work remaining are represented; it is invariant under arbitrary linear transformations of the state space coordinates, and therefore is robust concerning different estimation and measurement procedures of the project managers. (6) The measure is derived from first principles on the basis of Grassberger's seminal complexity theory and was not heuristically constructed. Therefore, the construct validity can not put into question. The supplementing slides show more details on the cited properties, give a closed-form solution for two tasks in the spectral basis and clarify the relationship between the key performance indicator "total work in CE project" and *EMC*.

4 VALDITION STUDY

In order to validate both the stochastic project model from eq. 1 and the novel complexity measure from eq. 2 a field study in a small-sized company of the German industry was conducted. The company develops advanced sensor technologies for automotive suppliers. To deal with a valid business case, the work of three engineers in a multiproject setting with three development projects, A, B and C was analyzed. The main project A had 10 development tasks, from the conceptual design of the regarded sensor to the product documentation for the customer and ran for 13 weeks. Projects B and C were "fast track projects" which both ran for less than 3 weeks. The acquired time data of task processing was very fine grained because the company used a barcode-based labor time system. In the supplementing slides the focus is on the initial two development tasks, (1) "conceptual sensor design" and (2) "design of circuit diagram" of project A. These tasks determine the total project costs to a large extent. The slides also show the results of a corresponding sensitivity analysis of *EMC*.

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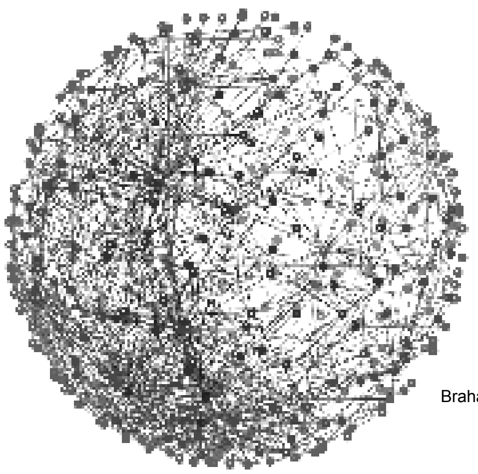
Complexity and Concurrent Engineering Projects

- Complexity →**Large number** of engineers in **multifunctional teams** who make **partially autonomous decisions** on product components, but also **strongly interact** in their overall impact on project performance
- CE projects →networks of **tightly coupled** and **concurrent tasks** with **frequent iterations among actors** plus **performance fluctuations**



- Graph depicts network of information flows between tasks of a development project
- The task network consists of 1245 directed information flows between 466 (overlapping) tasks
- Each task is assigned to one or more actors (individual or team)

Braha & Bar Yam 2007

Technische Universität München

Dynamic Models of Concurrent Engineering Projects (I)

1. Deterministic Model: $\mathbf{x_t} = \mathbf{A_0} \cdot \mathbf{x_{t-1}}$ $\quad \mathbf{x_0} = (1 \quad 1 \quad \ldots)^T$

Smith & Eppinger (1997)

$\mathbf{x_t}$: work remaining in time slice t
$\mathbf{x_0}$: initial work remaining

Design Structure Matrix
Lucas et al. (2007)

Work Transformation Matrix (WTM)
Huberman & Wilkinson (2005)

$$
\begin{array}{lll}
 & & \begin{array}{ccccc} \text{A} & \text{B} & \text{C} & \text{D} & \text{E} \end{array} \\
\text{A} & \text{Def. module function} & \\
\text{B} & \text{Def. electronic function} & \\
\text{C} & \text{Def. software function} & \\
\text{D} & \text{Def. mechanical function} & \\
\text{E} & \ldots &
\end{array}
\left(\begin{array}{ccccc}
\text{(X)} & \text{X} & \text{X} & \text{X} & \ldots \\
\text{X} & \text{(X)} & \text{X} & \text{X} & \\
\text{X} & \text{X} & \text{(X)} & \text{X} & \\
\text{X} & \text{X} & \text{X} & \text{(X)} & \\
\ldots & & & &
\end{array}\right)
\longrightarrow
\mathbf{A_0} = \begin{pmatrix} 0.90 & 0.05 & 0.01 & 0.01 \\ 0.05 & 0.81 & 0.05 & 0.01 \\ 0.01 & 0.05 & 0.72 & 0.05 \\ 0.01 & 0.01 & 0.05 & 0.70 \end{pmatrix}
$$

a_{ii}: autonomous task processing rates
a_{ij}: rework parameters

Calculation of work remaining for distinct time slices t = 1, 2, … with the WTM $\mathbf{A_0}$:

$$\mathbf{x_1} = \mathbf{A_0} \cdot \mathbf{x_0} \qquad = (0.97 \quad 0.92 \quad 0.83 \quad 0.77)^T$$
$$\mathbf{x_2} = (\mathbf{A_0})^2 \cdot \mathbf{x_0} = (0.94 \quad 0.84 \quad 0.69 \quad 0.60)^T$$
$$\mathbf{x_3} = (\mathbf{A_0})^3 \cdot \mathbf{x_0} = (0.90 \quad 0.77 \quad 0.58 \quad 0.47)^T$$
…

Dynamic Models of Concurrent Engineering Projects (II)

2. Stochastic Model: $\mathbf{x_t} = \mathbf{A_0} \cdot \mathbf{x_{t-1}} + \mathbf{S_t}$ $\quad \mathbf{x_0} = (1 \quad 1 \quad \ldots)^T$ $\quad \mathbf{S_t} \sim Normal(\vec{0}, \mathbf{\Sigma_s})$

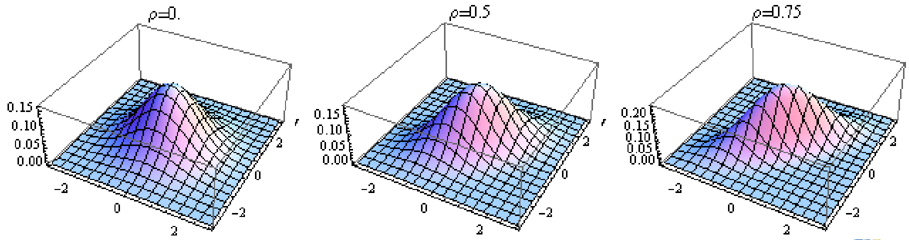
Schlick (2007)

Linear stochastic difference equation. Random variable $\mathbf{S_t}$ models individual performance variability and non-predictable fluctuations of business environment $\Rightarrow$CE project is an **open organizational system**. The means of work remaining evolve unperturbed. $\mathbf{S_t}$ has covariance matrix $\mathbf{\Sigma_S}$ representing fluctuation strength s_i of tasks and their correlations ρ_{ij}.

Parametric example for two tasks:

$$\mathbf{A_0} = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \qquad \mathbf{\Sigma_s}(s_1, s_2, \rho) = \begin{pmatrix} (s_1 \cdot a_{11})^2 & \rho \cdot (s_1 \cdot a_{11}) \cdot (s_2 \cdot a_{22}) \\ \rho \cdot (s_1 \cdot a_{11}) \cdot (s_2 \cdot a_{22}) & (s_2 \cdot a_{22})^2 \end{pmatrix}$$

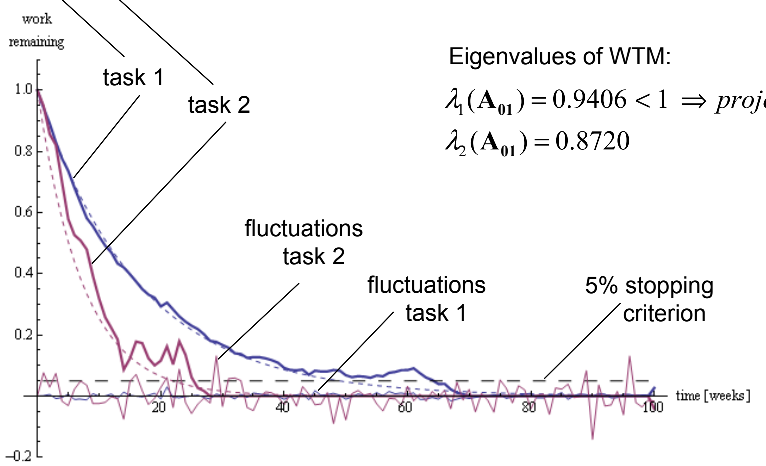
The correlation coefficient ρ has the following effect on the probability density of $\mathbf{S_t}$:



Traces of Project Dynamics (I)

The stochastic model is able to represent different project organizations, e.g.
1) **Uncoupled** concurrent tasks → decaying geometric series with small fluctuations

$$\mathbf{A}_{01} = \begin{pmatrix} 0.9406 & 0 \\ 0 & 0.8720 \end{pmatrix} \qquad \boldsymbol{\Sigma}_s(s_1 = 0.01, s_2 = 0.04, \rho = 0) = \begin{pmatrix} (0.01 \cdot 0.9406)^2 & 0 \\ 0 & (0.04 \cdot 0.8720)^2 \end{pmatrix}$$



Eigenvalues of WTM:

$\lambda_1(\mathbf{A}_{01}) = 0.9406 < 1 \;\Rightarrow\; \textit{project converges}$

$\lambda_2(\mathbf{A}_{01}) = 0.8720$

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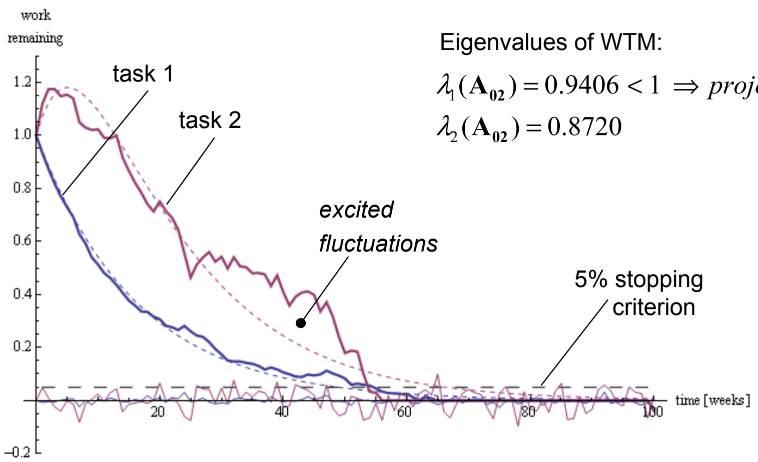
Traces of Project Dynamics (II)

2) Only **forward coupled** tasks → overshoot of work remaining plus excited fluctuations

$$\mathbf{A}_{02} = \begin{pmatrix} 0.9406 & 0 \\ 0.2 & 0.8720 \end{pmatrix} \qquad \boldsymbol{\Sigma}_s(s_1 = 0.01, s_2 = 0.04, \rho = 0) = \begin{pmatrix} (0.01 \cdot 0.9406)^2 & 0 \\ 0 & (0.04 \cdot 0.8720)^2 \end{pmatrix}$$



Eigenvalues of WTM:

$\lambda_1(\mathbf{A}_{02}) = 0.9406 < 1 \;\Rightarrow\; \textit{project converges}$

$\lambda_2(\mathbf{A}_{02}) = 0.8720$

Traces of Project Dynamics (III)

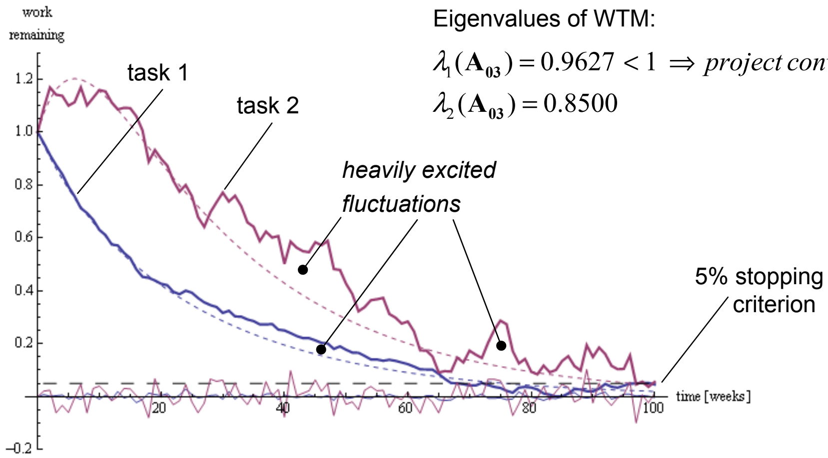
3) **Forward** and **backward coupled** tasks → overshoot plus heavily excited fluctuations

$$\mathbf{A}_{03} = \begin{pmatrix} 0.9406 & 0.01 \\ 0.2 & 0.8720 \end{pmatrix} \qquad \mathbf{\Sigma}_s(s_1 = 0.01, s_2 = 0.04, \rho = 0) = \begin{pmatrix} (0.01 \cdot 0.9406)^2 & 0 \\ 0 & (0.04 \cdot 0.8720)^2 \end{pmatrix}$$

Eigenvalues of WTM:

$\lambda_1(\mathbf{A}_{03}) = 0.9627 < 1 \;\Rightarrow\; \textit{project converges}$

$\lambda_2(\mathbf{A}_{03}) = 0.8500$

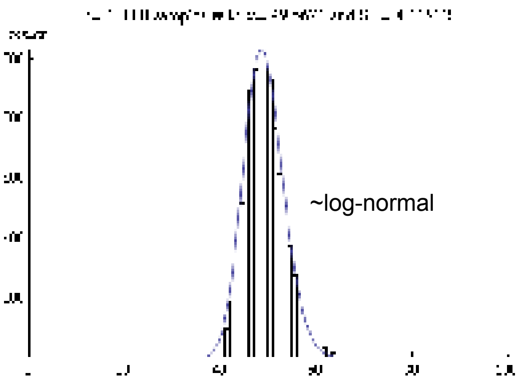


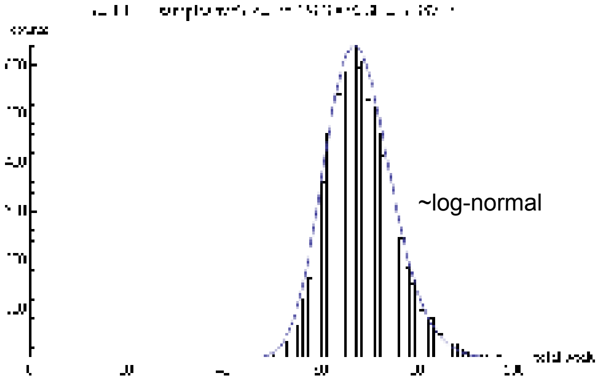
Excitation of Fluctuations: Comparison of Cases II and III

The additional tiny backward task coupling of 0.01 in each time slice has a very large effect on **both average and standard deviation** of total work* to be done in CE project

$$\mathbf{A}_{02} = \begin{pmatrix} 0.9406 & 0 \\ 0.2 & 0.8720 \end{pmatrix} \qquad \mathbf{A}_{03} = \begin{pmatrix} 0.9406 & 0.01 \\ 0.2 & 0.8720 \end{pmatrix}$$

$\mathbf{\Sigma}_s$ *as in previous slides*



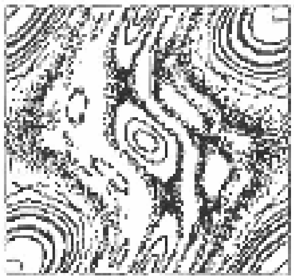
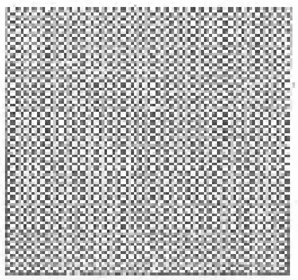
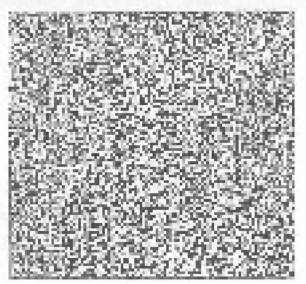


*the key performance indictor “total work” represents the accumulated work remaining for both tasks 1 and 2 until the stopping criterion is met and the simulated project is finished.

Scientific Complexity Theory

- Physicist P. Grassberger developed a seminal complexity theory of open dynamic systems which has not been considered in engineering and complexity management before
- His work is the foundation of novel DSM-based complexity measure for CE projects, which is called the ***Effective Measure Complexity (EMC)***
- ***EMC*** counts the amount of information required for optimal prediction of project dynamics; it can discover long and short range interactions between tasks and is able to deal with emergent complexity due to excited fluctuations

complex pattern EMC_1 >> *regular* EMC_2 > *random (perfect chaos)* $EMC_3 = 0$

Grassberger 1986

Effective Measure Complexity of Project Dynamics

Computed complexity measure for stochastic CE project model (in stationary state):

$$EMC = \frac{1}{2}\log_2\left(\frac{\det\left(\sum_{k=0}^{\infty}\mathbf{A_0}^k \cdot \mathbf{\Sigma_s} \cdot (\mathbf{A_0}^T)^k\right)}{\det\left(\mathbf{\Sigma_s}\right)}\right)$$

Beside its mathematical beauty the novel complexity measure ***EMC***…

1. …is small for CE projects with uncoupled tasks and large for complex projects with multiple and strong task couplings
2. …unambiguously shows the bound of project stability by assigning infinite complexity values to diverging projects (that is $\lambda_{max}(\mathbf{A_0}) > 1$)
3. …assigns larger complexity values to projects with more tasks if the task couplings are similar, and therefore it is sensitive to the cardinality of the project
4. …is able to cope with fluctuations and performance variability in project dynamics
5. …is independent of the basis in which the project state vectors are represented and invariant under arbitrary linear transformations of the state space coordinates
6. …is derived from first principles and is not heuristically constructed.

Effective Measure Complexity – Some Details on Properties (I)

EMC…

1. …is small for CE projects with uncoupled tasks and large for complex projects with multiple and strong task couplings:

$$\mathbf{A}_{01} = \begin{pmatrix} 0.9406 & 0 \\ 0 & 0.8720 \end{pmatrix} \Rightarrow EMC = 2.59$$

$$\mathbf{A}_{02} = \begin{pmatrix} 0.9406 & 0 \\ 0.2 & 0.8720 \end{pmatrix} \Rightarrow EMC = 2.63$$

$$\mathbf{A}_{03} = \begin{pmatrix} 0.9406 & 0.01 \\ 0.2 & 0.8720 \end{pmatrix} \Rightarrow EMC = 2.81$$

note that increase of *EMC* by 1 represents doubling of information being communicated to the future, because $\log_2(.)$ has base 2!

$$with\ \ \mathbf{\Sigma}_s = \begin{pmatrix} (0.01 \cdot 0.9406)^2 & 0 \\ 0 & (0.04 \cdot 0.8720)^2 \end{pmatrix}$$

Effective Measure Complexity – Some Details on Properties (II)

EMC…

2. …unambiguously shows the bound of project stability by assigning infinite complexity values to diverging projects (that is $\lambda_{max}(\mathbf{A_0}) > 1$):

This proposition can be proved easily for the case of uncoupled tasks:
If the p tasks of a CE project are uncoupled (that is $a_{ij} = 0$ for all $i \neq j$; $i, j = 1 \dots p$), the eigenvalues λ_i of $\mathbf{A_0}$ are equal to the autonomous work progress rates a_{ii}.
If furthermore the fluctuations are uncorrelated (that is $\rho_{ij} = 0$ in $\mathbf{\Sigma_S}$ for all $i \neq j$), *EMC* can be fully simplified:

$$EMC = \frac{1}{2}\sum_{i=1}^{p}\log_2 \frac{1}{1-\lambda_i(\mathbf{A}_0)^2} = \frac{1}{2}\sum_{i=1}^{p}\log_2 \frac{1}{1-a_{ii}^{\ 2}} \qquad \lambda_i(\mathbf{A}_0)\ \ i\text{-}th\ Eigenvalue\ of\ \ \mathbf{A}_0$$

Clearly, $EMC \to \infty$ if $\lambda_{max}(\mathbf{A_0}) \to 1$

The proposition also holds for arbitrary work transformation matrices $\mathbf{A_0}$ and covariance matrices $\mathbf{\Sigma_S}$!

Effective Measure Complexity – Some Details on Properties (III)

EMC…

5. …is independent of the basis in which the project state vectors are represented and invariant under arbitrary linear transformations of the state space coordinates:

For only two tasks (p = 2) one can find a simple closed solution for *EMC* in the spectral basis. Therefore, the WTM $\mathbf{A_0}$ is decomposed by a basis of eigenvectors, given as the columns of the matrix **S** and a diagonal matrix Λ with the eigenvalues λ_i:

$$\mathbf{A_0} = S\Lambda S^{-1} \quad with \quad \Lambda = diag\left(\lambda_i(\mathbf{A_0})\right)$$

In the spectral basis one can analyze the project dynamics as a set of uncoupled linear processes with correlated noise (coefficient ρ'). We assume that both eigenvalues λ_1 and λ_2 are real. In this case the closed form solution is:

$$EMC = \frac{1}{2}\left(\log_2 \frac{1}{1-\lambda_1^2} + \log_2 \frac{1}{1-\lambda_2^2} + \log_2\left(1 + \frac{\rho'^2}{1-\rho'^2}\frac{(\lambda_1-\lambda_2)^2}{(1-\lambda_1\lambda_2)}\right)\right)$$

Compare *EMC* with the closed form solution of the key performance indicator "total work" in the deterministic case with uncoupled tasks and discover the similarities:

$$TotalWork = \sum_{t=0}^{\infty}(\mathbf{A_0})^t \cdot x_0 = \sum_{t=0}^{\infty} a_{11}{}^t + \sum_{t=0}^{\infty} a_{22}{}^t = \sum_{t=0}^{\infty}\lambda_1{}^t + \sum_{t=0}^{\infty}\lambda_2{}^t = \frac{1}{1-\lambda_1} + \frac{1}{1-\lambda_2}$$

Validation Study in Industry

- Field study in a small company of the **German automotive supplier industry**
  - Considered project 1 was on the design of a mechatronic acceleration sensor with three engineers and 10 tasks
  - Highly parallel task processing and frequent iterations among subtasks
  - Very accurate project time data was available, because of the use of a barcode-based labor time system (resolution of one minute!).
- Focus on the initial two development tasks of the considered project
  task 1: "conceptual sensor design"
  task 2: "design of circuit diagram"
- Estimated parameters from historical data through maximum likelihood estimator:

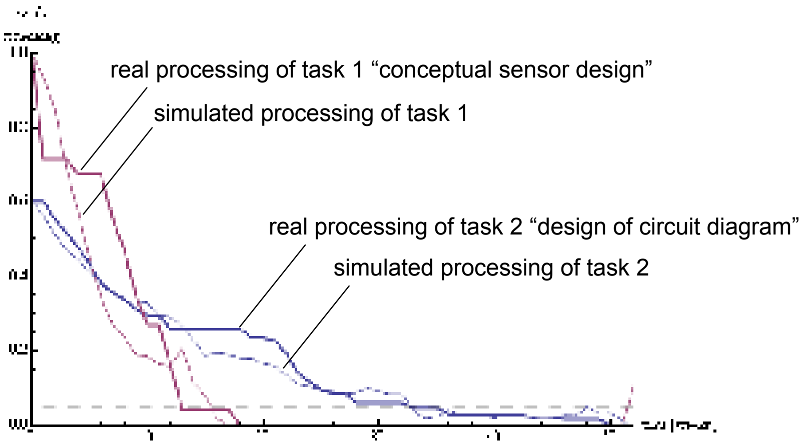
estimated WTM $\mathbf{A_{0case}} = \begin{pmatrix} 0.9406 & -0.00169 \\ 0.00846 & 0.8720 \end{pmatrix}$

estimated initial work remaining $\mathbf{x_{0case}} = \begin{pmatrix} 0.6 \\ 1 \end{pmatrix}$

estimated fluctuations $\mathbf{\Sigma_s}(s_1 = 0.0144, s_2 = 0.0477, \rho = -0.3833)$

Validation Study – Comparison of Project Dynamics

The real work progress is quite similar to the simulated:



Validation Study – Sensitivity Analysis (I)

- Only structural validation of *EMC* was possible, because there were only three company specific CE projects analyzed in detail

→ **Sensitivity analysis of complexity measure for tasks 1 and 2 of most complex project 1**

- Therefore, the off-diagonal elements of the WTM $\mathbf{A_{0case}}$ were not “clamped”, but two rework parameters a_{12} and a_{21} - varying between 0 and 1 - were introduced:

$$\mathbf{A}_{\mathbf{0case}} = \begin{pmatrix} 0.9406 & a_{12} \\ a_{21} & 0.8720 \end{pmatrix}$$

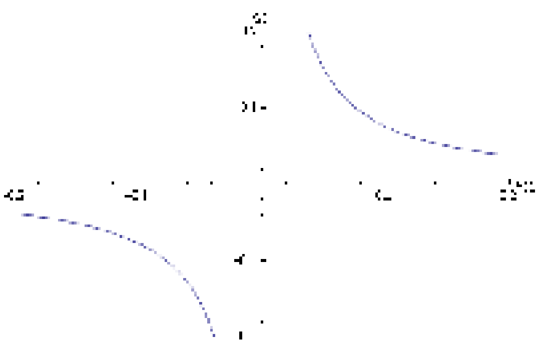
- Computed stability bound based on eigenvalue analysis:

$$a_{12} \cdot a_{21} \overset{!}{=} (0.9406-1) \cdot (0.8720-1) \Leftrightarrow a_{12} \cdot a_{21} \overset{!}{=} 0.0076$$
$$\text{If } a_{12} \cdot a_{21} > 0.0076 \Rightarrow \text{project is divergent}$$
$$\text{If } a_{12} \cdot a_{21} < 0.0076 \Rightarrow \text{project is convergent}$$

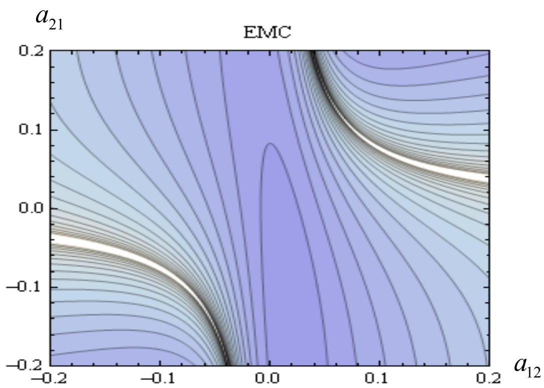
Validation Study – Sensitivity Analysis (II)

Stability bound for considered tasks 1 and 2 of CE project 1 based on eigenvalue analysis:

$$a_{12} \cdot a_{21} = 0.0076$$



Contour plot of computed *EMC* values for varying rework parameters a_{12} and a_{21} of the WTM $\mathbf{A_{0case}}$ (Σ_S as before):



Future Work and Acknowledgement

- More simulation and validation studies of the novel complexity measure *EMC* in the German industry
- Development of an ergonomic software tool for integrative modeling, simulation and complexity assessment of NPD projects
- Complexity study of multiplicative noise $\mathbf{S}_t$ instead of additive noise which was pioneered by Huberman & Wilkinson (2005):
  - Calculate probability distributions in steady state
  - Calculate dynamic entropies for steady state distributions and derive the associated complexity measure *EMC*.

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