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Mechanisms of Instability in Small-Scale Manufacturing Networks

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BIBA Bremen Institute of Industrial Technology and Applied Work Science at the University of Bremen

Production logistics research in the traffic modelling group

- Apply knowledge from traffic sciences to transportation and production logistics
- Industrial projects (SCA packaging, VW) and fundamental research projects (DFG, EU, Volkswagen foundation, DB foundation) on production and logistics
- Mathematical modelling of logistic processes in transport and production (fluid-dynamic, heterogeneous multi-agents, hybrid models,...)
- Stability analysis and understanding of complex temporal dynamics
- Interrelationships of structural network properties and dynamic instabilities in production systems
- Development of new data analysis methods for characterizing the performance of logistic systems

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1. Motivation

Globalization: manufacturers must flexibly and fastly adapt to changing market conditions

$\Rightarrow$ Increasing complexity of decision processes, diversification of products

Possible reaction: Outsourcing / concentration on core competences, i.e., specialization

$\Rightarrow$ Economic networks of large complexity and size

Consequence: increasing complexity of real-world manufacturing systems

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1. Motivation

Negative effects: production breakdowns (lack of material), instabilities (Bullwhip effect,...) etc.

Possible approaches:

- Decoupling of business units: large buffers (highly unflexible!)
- Just-in-time logistics: strong coupling between selected business units – complex networks with „irregular“ dynamics

Aim: understand irregular/unstable dynamics of manufacturing networks by sophisticated analysis of simulation models

Models of real-world manufacturing networks

Approach 1: continuous-time models (fluid-dynamic approach) – well suited for studying general features, but: implementation of specific network structures and dynamics often rather complicated

Approach 2: event-discrete simulations – detailed and realistic implementation of production mechanisms in (commercial) software packages (here: eM-Plant 7.5)

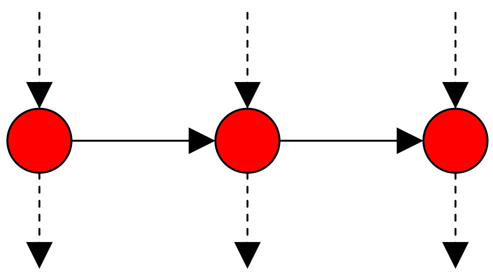
Main sources of instability:

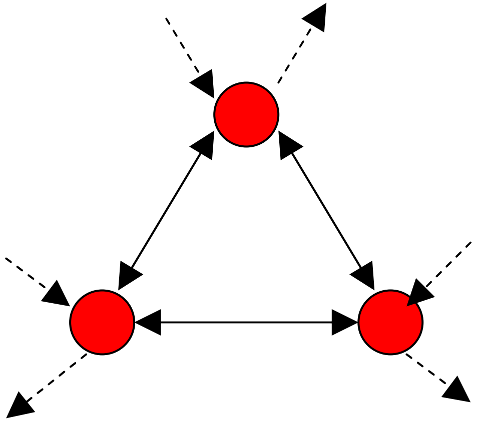
- Complicated external demand/supply variability
- Complicated structure of interactions between manufacturers (e.g., feedback loops of material and/or information flows)

  <u>Limiting cases:</u>

  - linear supply chains (no feedback of material flows)

  - symmetrically interacting manufacturers (i.e., network with „all-to-all“ material flows)





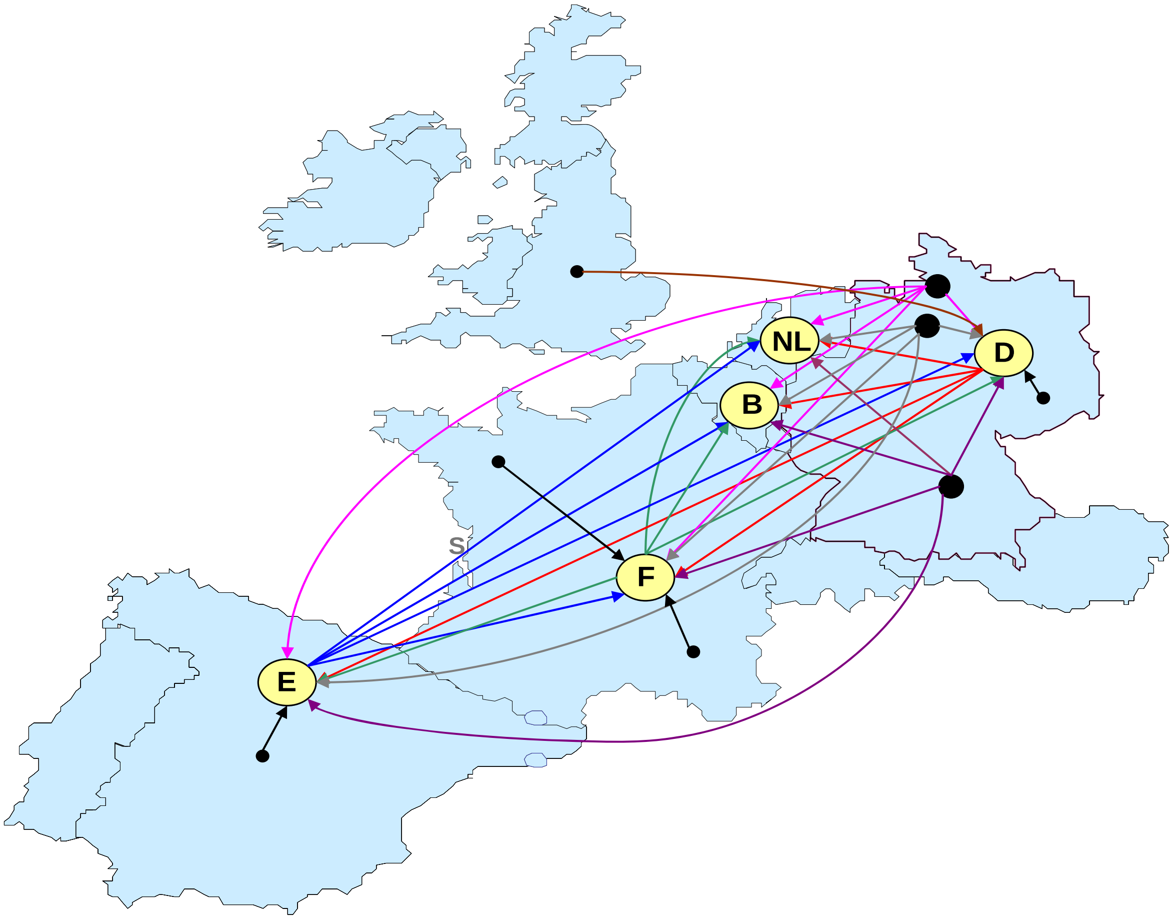
Instabilities in manufacturing networks:

may already occur in small-scale systems (only very few nodes)

$\Rightarrow$ more efficient simulation: N=2 to 4 nodes

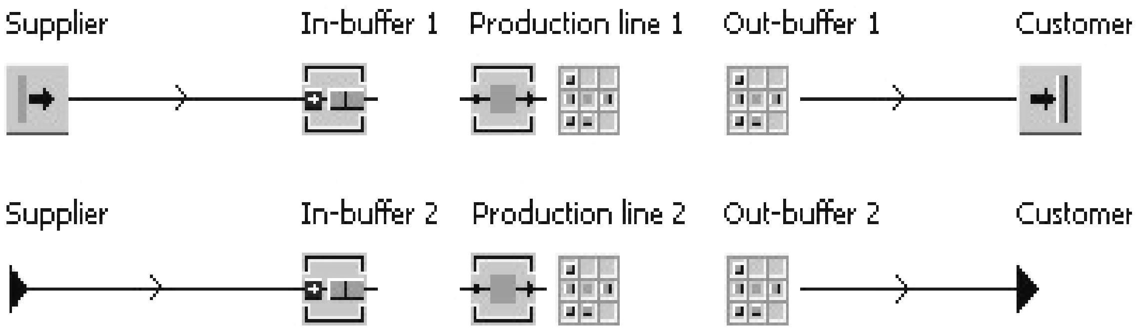
Is this a reasonable assumption?

Real-world example



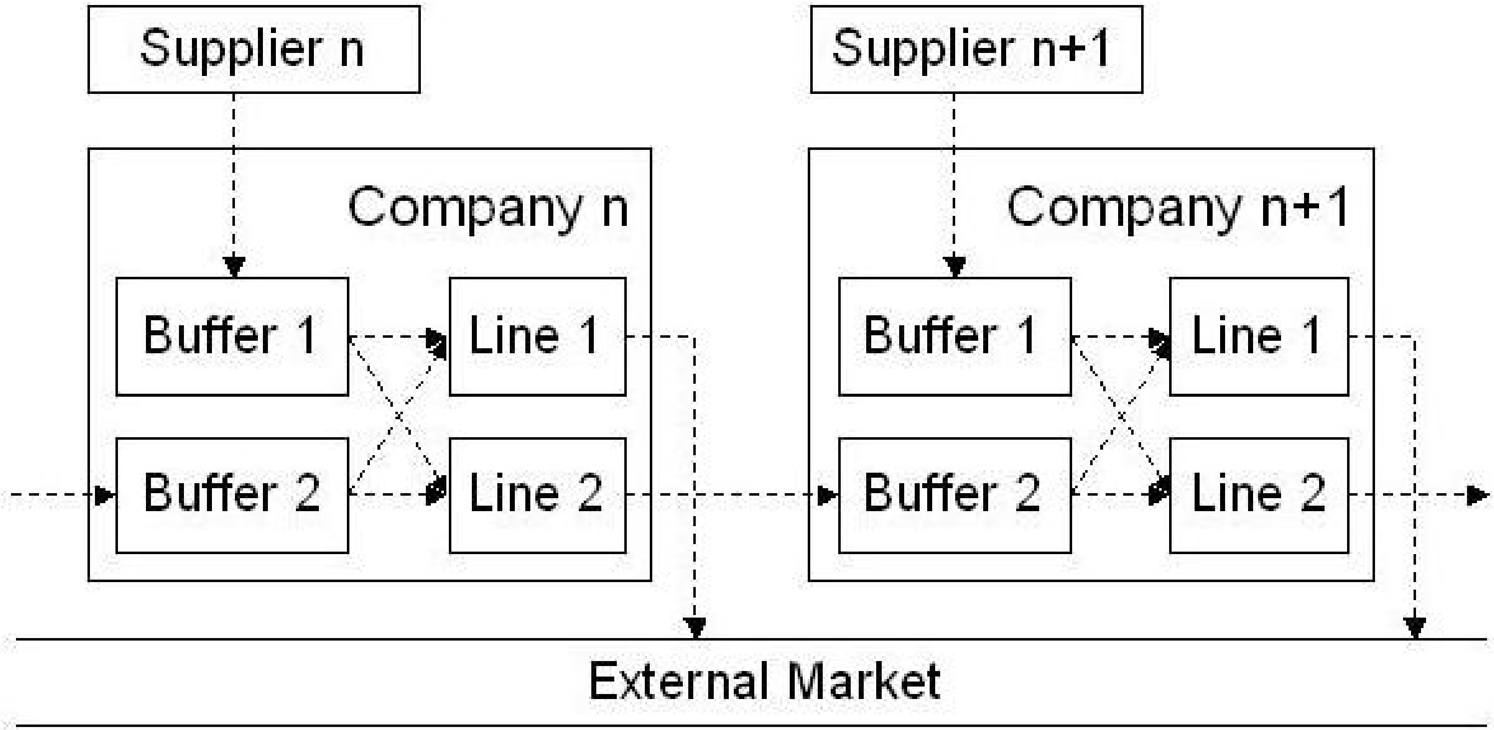
2. Implementation of Simulation Model

eM-Plant: graphical combination of different predefined modules
+ interfaces for on-line monitoring of simulation

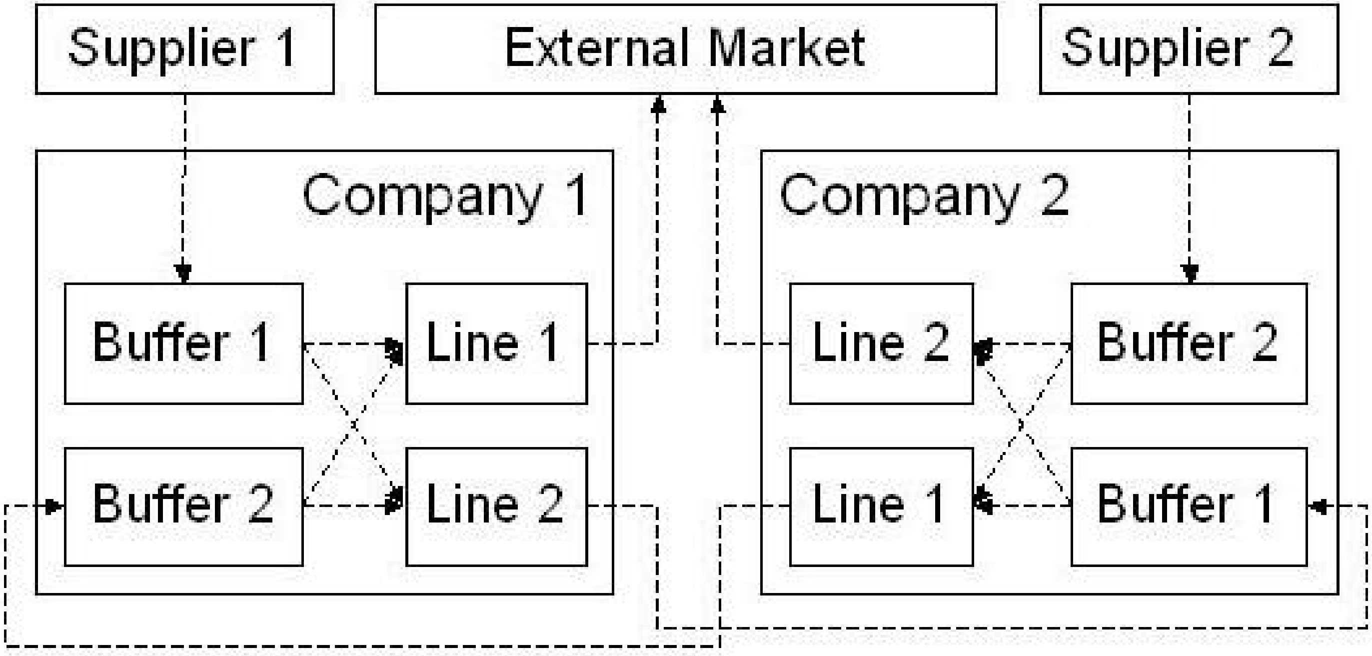


⇒ Definition of supply lines, production strategies (sub-models), time scales for production and transportation, order volumes, production matrices etc.

Case I: Linear Supply Chain



Case II: Symmetrically Interacting Companies



Model Variants

I. Fixed vs. distributed processing times (basic clock or stochastic distribution of „events“)

II. Production strategies: pull vs. push

III. Order policies: provision, order point, and periodic order policies

IV. Number of nodes

V. Network topology (linear chain vs. symmetric coupling)

VI. Variation of parameters (time scales, lot sizes)

3. Challenges for Time Series Analysis

Observed logistic quantities: inventory levels (stocks) – allow to derive other meaningful observables like throughput times, waiting times, reliability of delivery dates,...

Some essential problems:

a) non-uniform timing of events

b) nonlinearities/irregularities

c) integer quantities (!)

$\Rightarrow$ Require specific methods of analysis

Symbolic Time Series Analysis

Consider integer values as symbols a from a discrete alphabet A

$\Rightarrow$ allows computation of different „linear“ as well as non-linear measures:

* symbolic correlation functions $$C_{XY}(\tau) = \sum_{a \in A} P_{aa}^{XY}(\tau)$$

* mutual information $$I_{XY}(\tau) = \sum_{a,b \in A} P_{ab}^{XY}(\tau) \log_2 \frac{P_{ab}^{XY}(\tau)}{P_a^X P_b^Y}$$

* entropies and derived measures of complexity

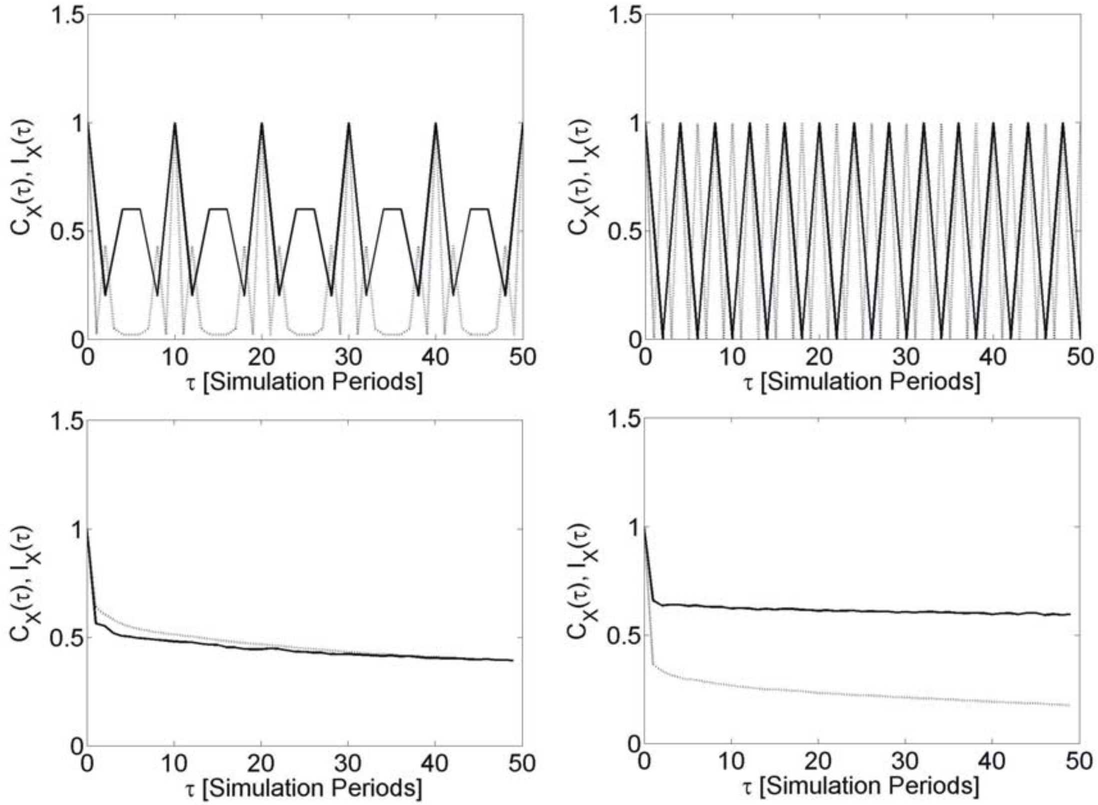
$$H_n = -\sum_{s^{(n)} \in A^n} P(x^{(n)} = s^{(n)}) \log P(x^{(n)} = s^{(n)})$$

Symbolic Time Series Analysis

Example:

periodic behaviour

irregular behaviour

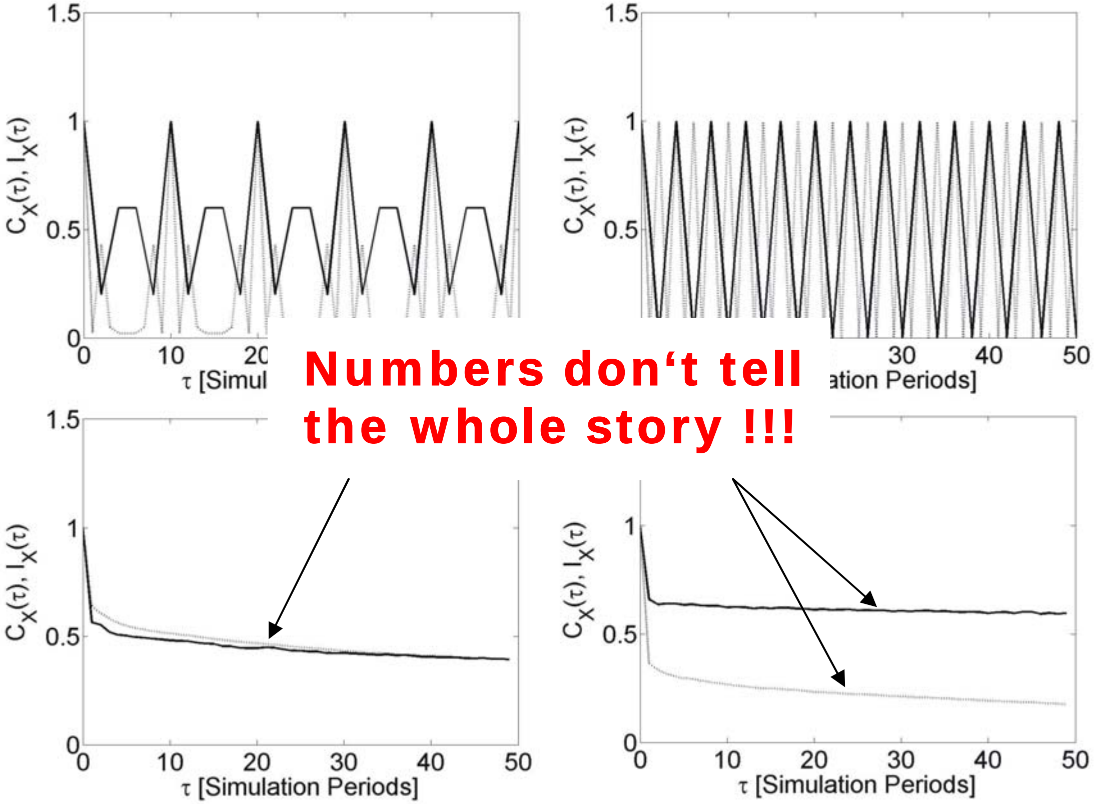


Symbolic Time Series Analysis

Example:

periodic behaviour

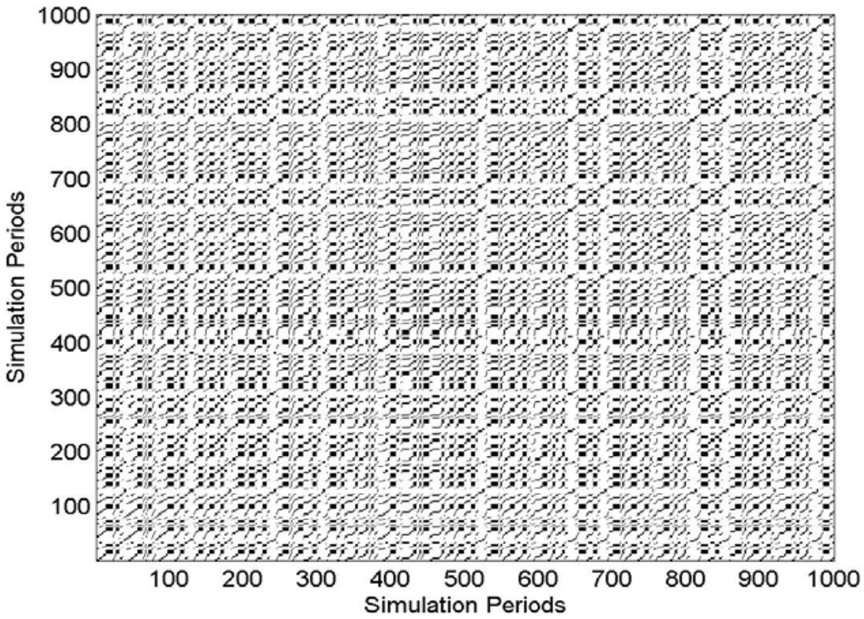
irregular behaviour



Recurrence Quantification Analysis

Original idea: visualization of topological structures within time series

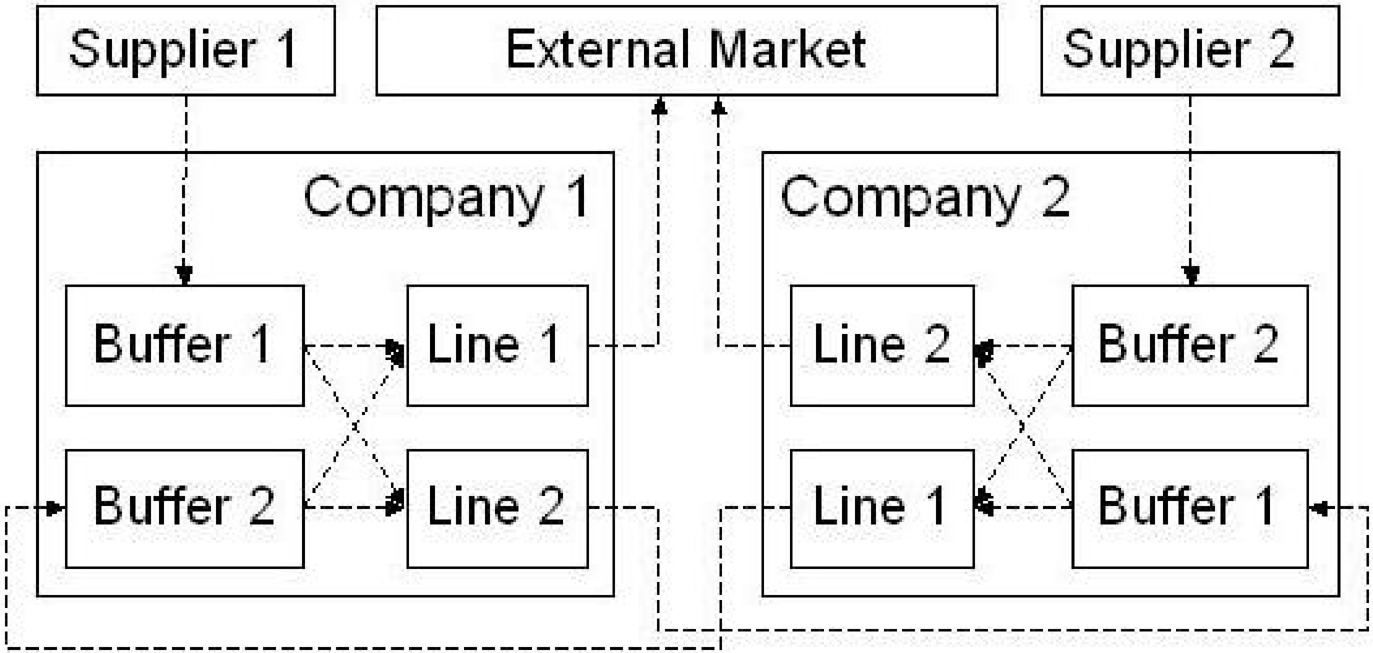
$$R_X(i, j) = \Theta\left(\varepsilon - \left\| X(i) - X(j) \right\|\right)$$



Statistics over diagonal or vertical structures:

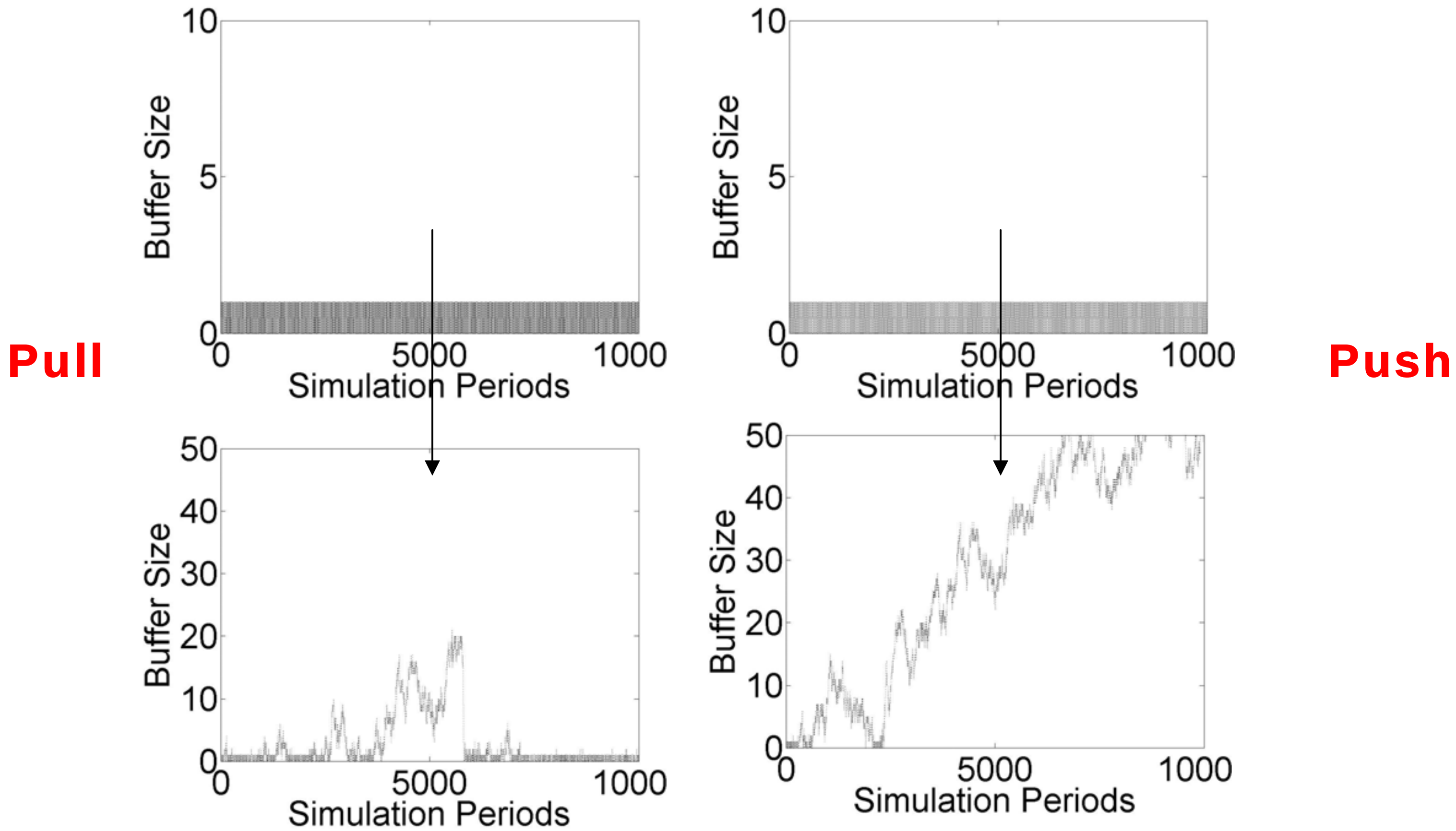
estimates for a variety of nonlinear characteristics (determinism, laminarity, entropy, correlation dimension, generalized mutual information,...)

4. Instability Mechanisms



Fluctuating Production Intervals

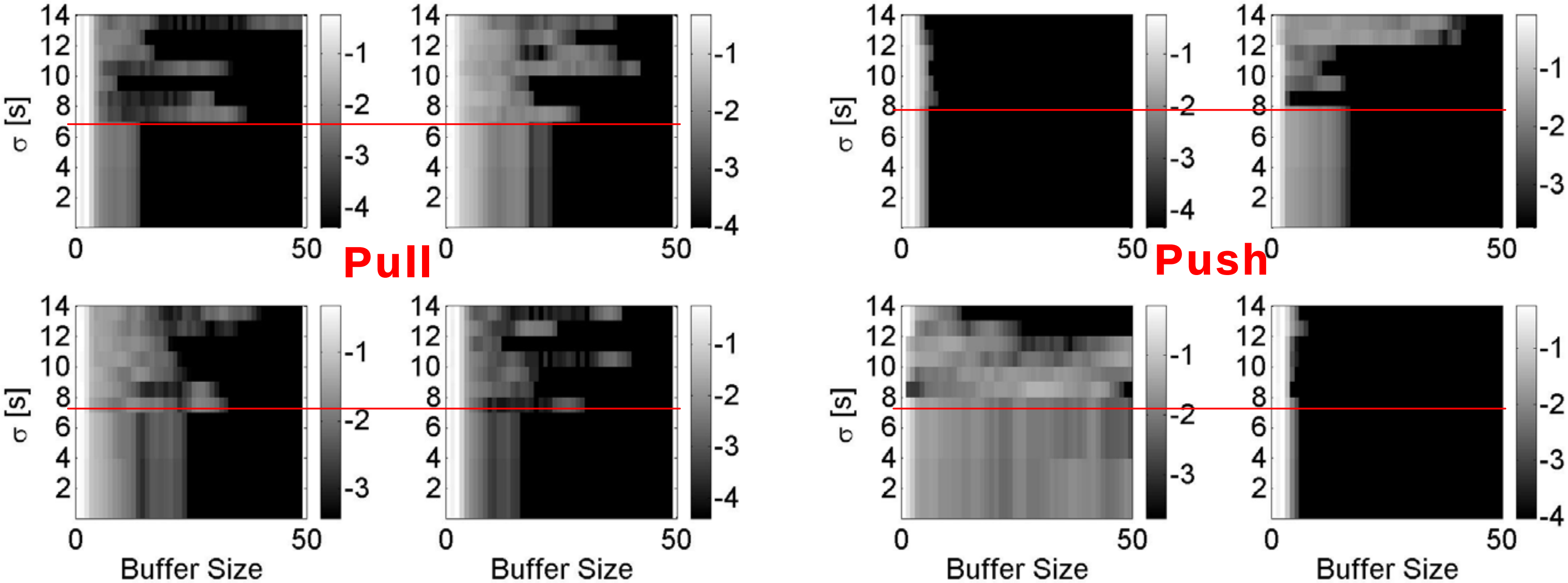
⇒ Intermittent accumulation of material in buffers



Fluctuating Production Intervals

⇒ Intermittent accumulation of material in buffers

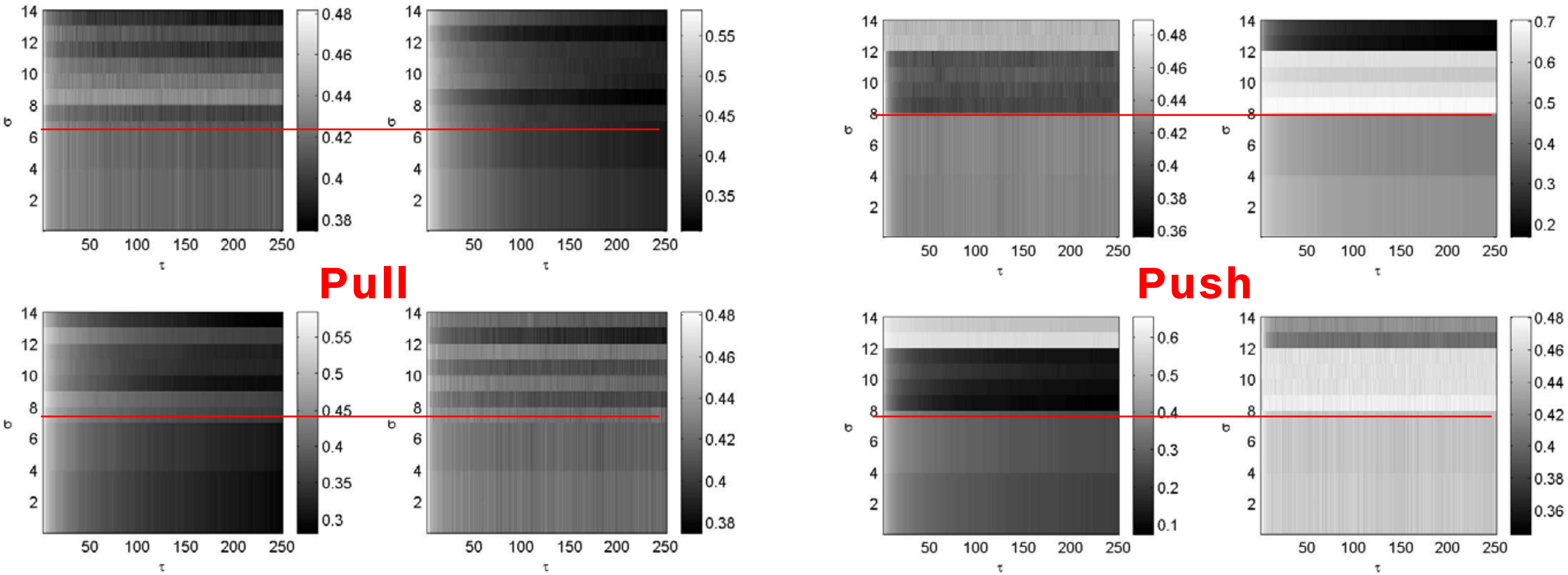
(logarithmic) histograms of stock levels (N=2):



Fluctuating Production Intervals

⇒ Intermittent accumulation of material in buffers

Symbolic auto-correlation functions of stock levels (N=2):



Imbalance of Material In- and Outflows

⇒ Unlimited accumulation of material in buffers in case of push strategy for large working-on-intervals

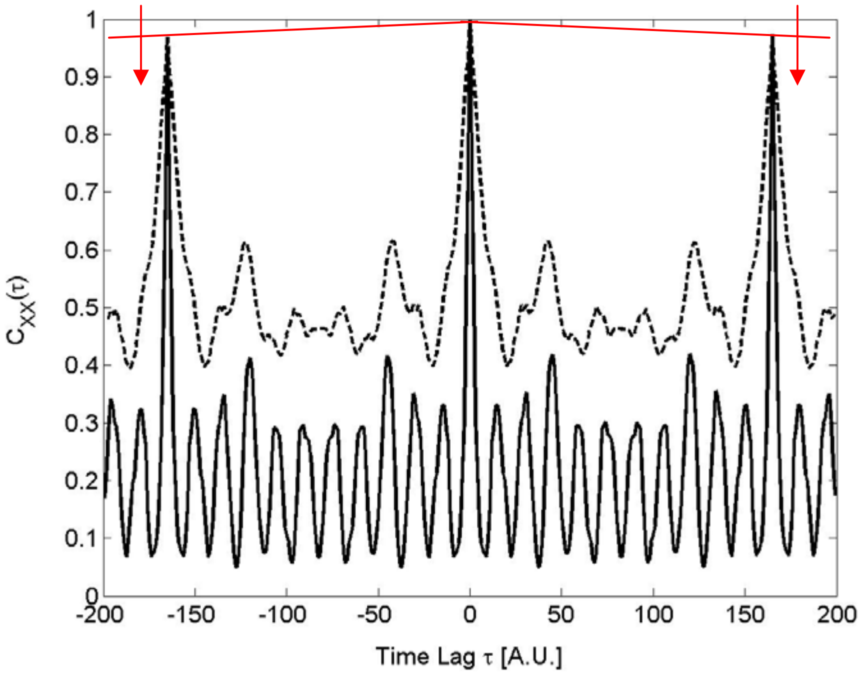
But: Stochasticity of production times may dramatically reduce this effect

* significant slowing of accumulation by a factor of 2-4,
* weakly unstable regime: even suppression of instability?

⇒ „Constructive“ effect of noise

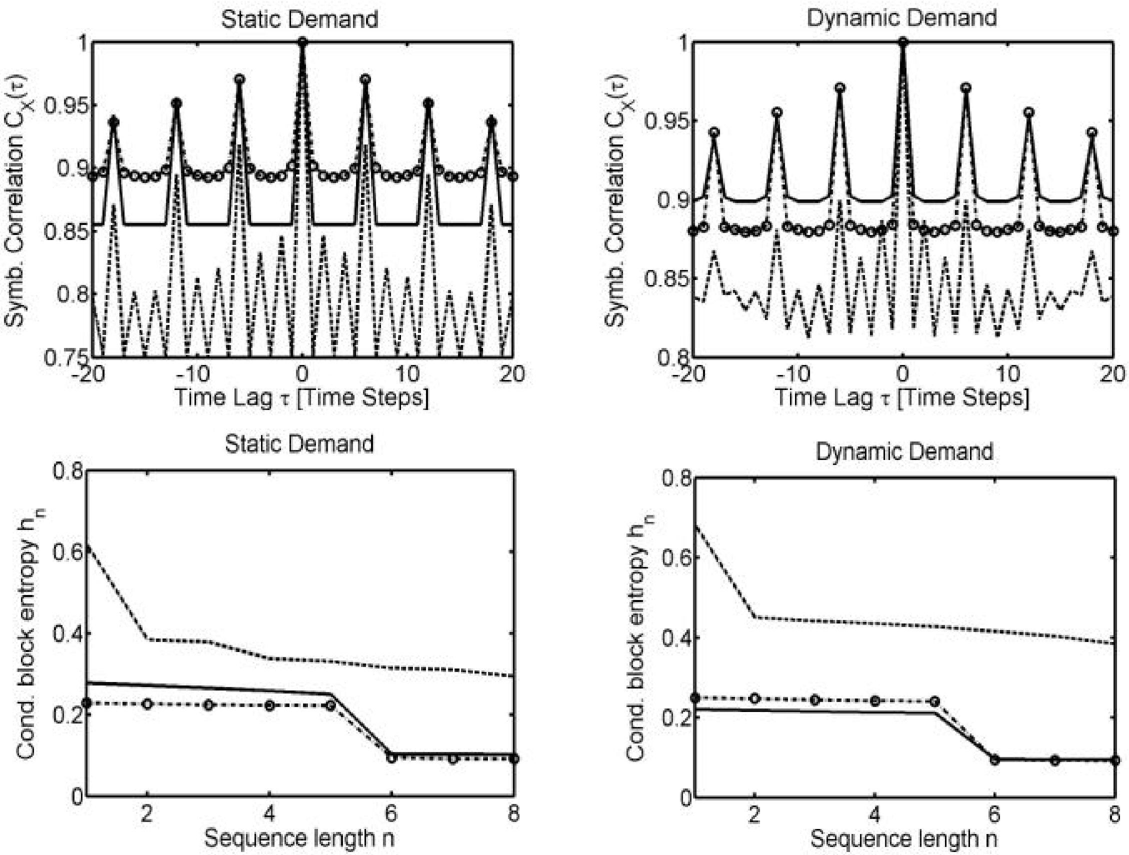
Incomplete Logistic Synchronization

⇒ Destruction of periodic production process for a pull strategy in the presence of improper lot sizes



Instability: periodic process becomes quasi-periodic or even chaotic to the presence of additional frequencies (torus decay scenario?)

Logistic Desynchronization due to Order Policies



o-o *provision policy:* fixed order volume in case of empty buffer (periodically checked)

—— *order point policy:* fixed order volume if buffer size is critical (periodically checked)

······ *periodic order policy:* periodic orders of variable size

5. Summary

Different mechanisms of instability in manufacturing networks:

Stochastic production times: almost independent on noise amplitude and parameters, intrinsic, intermittent accumulation of material

Imbalance of material flows (push): unlimited accumulation of material for large working-on-intervals, weakening/suppression in the presence of stochastic production times

Incomplete logistic synchronization (pull): increasing complexity due to individual order policies and/or improper lot sizes, transition to quasiperiodic or even chaotic behaviour

5. Summary

Work in progress:

quantification of dynamics by means of nonlinear measures (systematic parameter study)

mathematical model of the Bullwhip effect (including stability analysis) and dynamic production strategies for counteracting

validation of instabilities and their properties in fluid-dynamic models:

- stabilization by noise
- qualitative independence on noise amplitude
- bifurcation analysis (logistic desynchronization)

effects of network size in continuous-time and event-discrete models

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Thank you for your attention!