Chaos and complexity in SMEs networks and innovation ecosystems: post-pandemic challenges

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UNIVERSITÀ DEGLI STUDI DI MODENA E REGGIO EMILIA

Production and Systems Engineering Graduate Program - PPGEPS

Prof. Dr. Miguel Sellitto

Dottorato di Ricerca in Ingegneria dell´Innovazione Industriale - DISMI

Agenda

- Complexity theory:
  - General Systems Theory;
  - Chaos Theory;
  - Information Theory;
- Strategy in Networks
  - Typology;
  - Complexity Influence in the Strategy.

Complexity Theory: Systems, Chaos, Information

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Complexity Theory

- Elements of complexity theory are already found in the work of Greek philosophers, such as Plato (cybernetics) and Aristotle (teleology) and medieval philosophers, such as Roger Bacon (nature laws are shown by observation, not contemplation);
- The theory is currently considered to draw on key elements from three other theories developed in the 20th century:
  - General systems theory;
  - Chaos theory;
  - Information theory.

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Systems Theory

- The main subject encompasses the so-called CAS (complex adaptive systems);
- CAS evolve according to the auto-organization principle, in which parts exchange energy, materials, and information seeking for a suitable scheme that allows efficiently achieving their goals;
- The search can be controlled by a central intelligence or according to spontaneous, trial and error attempts.

Systems Theory

- Systems theory studies fundamental properties of networks based on non-linear interactions that can be direct or feedback (closed-loops);
- While negative feedback stabilizes the system, positive feedback can generate complex behavior that, if exceeding certain limits, generates chaotic behavior;
- An initial scheme, under uncertainty, engenders alternative schemes chosen by the intelligence, or unexpected schemes that emerge from the parts, stimulated by external information.

Elements of CAS

- Regular or unexpected interaction patterns are characterized by:
  - **Variety**: is the probability that any two agents can fulfill different missions;
  - **Flexibility**: is the probability that a single agent can fulfills more than one mission;
  - **Redundancy**: is the probability that more than one agent can fulfill a given mission;
  - **Availability**: is the probability that an agent will be idle when required for a mission;
  - **Reliability**: is the probability that at least one agent successfully accomplishes a given mission;
- More variety, more flexibility, more redundancy, more availability amplify the complexity and increase system´s reliability but also increase cost: a trade-off problem.

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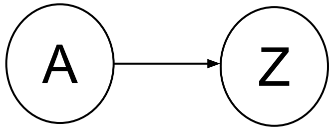
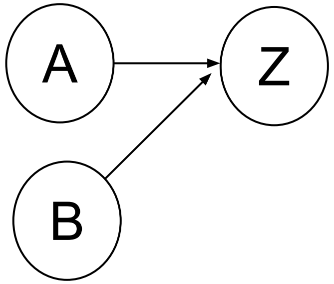
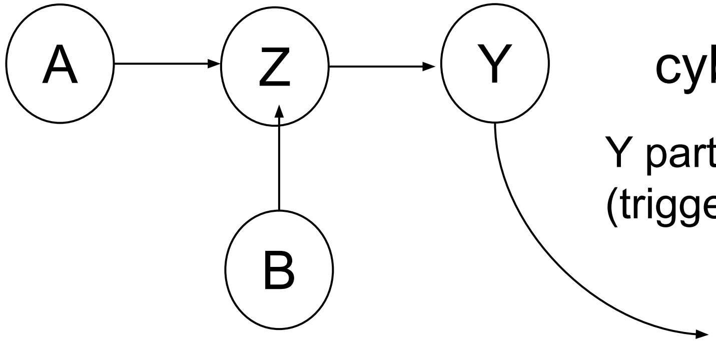
Linear and non-linear (complex) relationships



linear simple

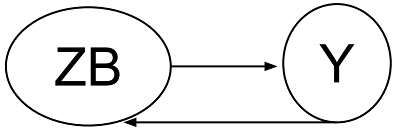


Linear multiple



cybernetics

Y partially causes itself
(triggered processes)



circularity

Y causes itself,
self-sustained process

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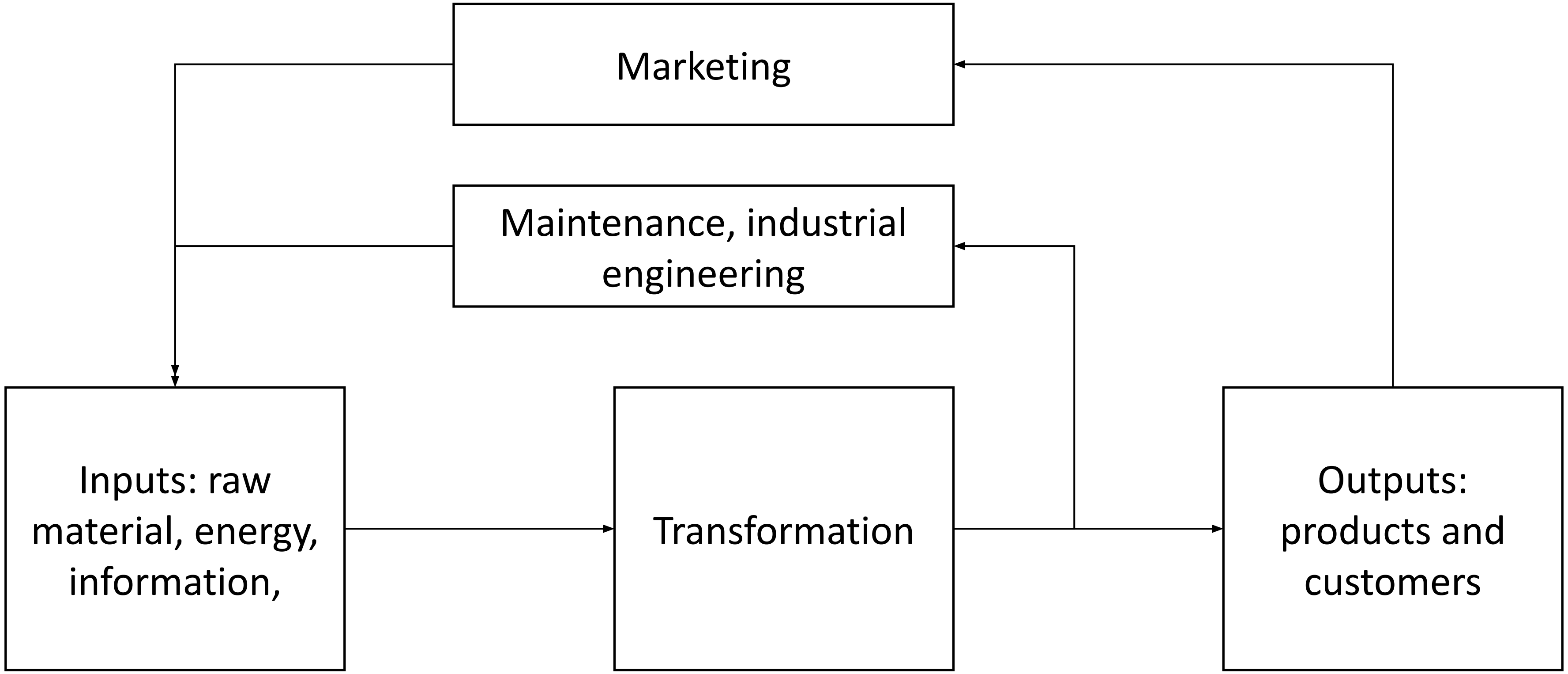
Manufacturing as a CAS

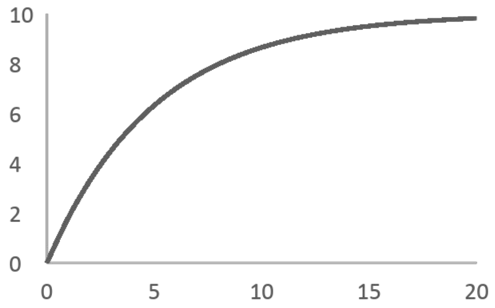


Chaos Theory

- Chaotic behavior originates from extreme responses of CASs which, under borderline conditions, exhibit unexpected behavior;
- Usually such behaviors are characterized by more than proportional variations in the output in response to small variations in the input;
- Such behaviors, at first sight, seem random but, observed in more depth, they result from a hidden, deterministic process;
- Therefore, one must consider that chaos is not synonymous with disorder, but with behavior that is difficult to decipher at first sight;
- The expressions "*chaos out of order*" and "*deterministic chaos*" are used in situations of extreme behavior of CASs.

Extreme behavior of systems

- First order: only negative feedback and quickly reach stability;



$$y(t) = k_1\left(1 - e^{-\frac{t}{k_2}}\right) \quad \text{(i)}$$

- Second order: negative as well as positive feedback may or may not reach stability;

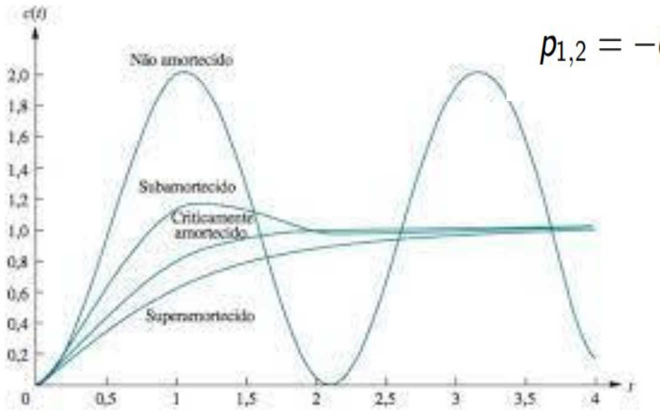
$$G(s) = \frac{K\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

$$p_{1,2} = -\sigma \pm j\omega_d$$

$$\sigma = \zeta\omega_n$$

$$\omega_d = \omega_n\sqrt{\zeta^2 - 1}$$

$$p_{1,2} = -\zeta\omega_n \pm j\omega_n\sqrt{\zeta^2 - 1}$$



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Extreme behavior of systems

- Chaotic: positive feedback loops may eventually convey to unstable states if a certain threshold is surpassed, the chaos edge;
- Theoretical models may be the only method of identifying chaotic behavior. If a chaotic trajectory can be described by a well-known model, with a given probability, it is possible to predict the next occurrence of the phenomenon.

Some well-known Chaotic Models

- Logistic Map (a second-order model, possibly the simplest);
- Tent Maps;
- Bernoulli Attractor;
- Hénon Attractor;
- Mackey-Glass Attractor;
- Lorenz Attractor.
- Application of the logistic map (https://www.sciencedirect.com/science/article/pii/S2405896318316161)

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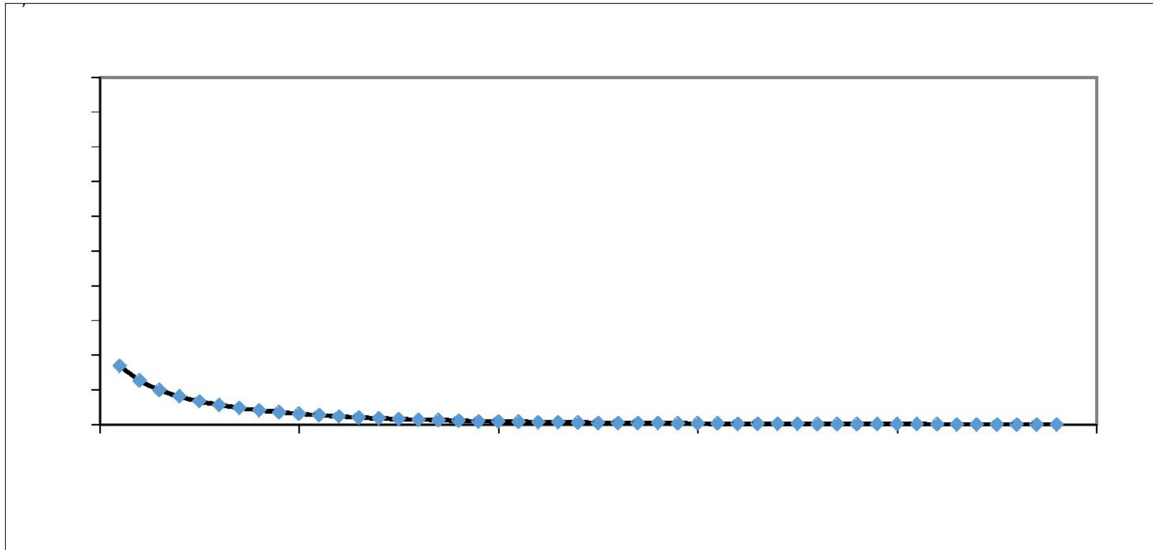
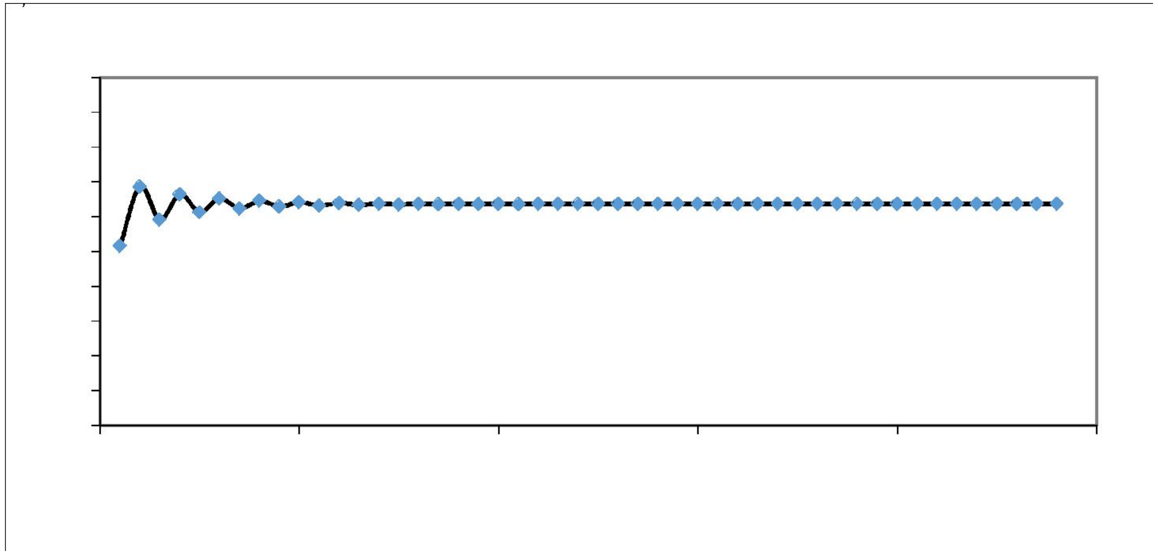
Logistic Map

- $x_{(t+1)} = ax_t(1 - x_t)$, if $4 > a > 0$.
- If $a < 1$, the outcome converges to zero;
  - a = 0,9, $x(0)$ = 0,75.



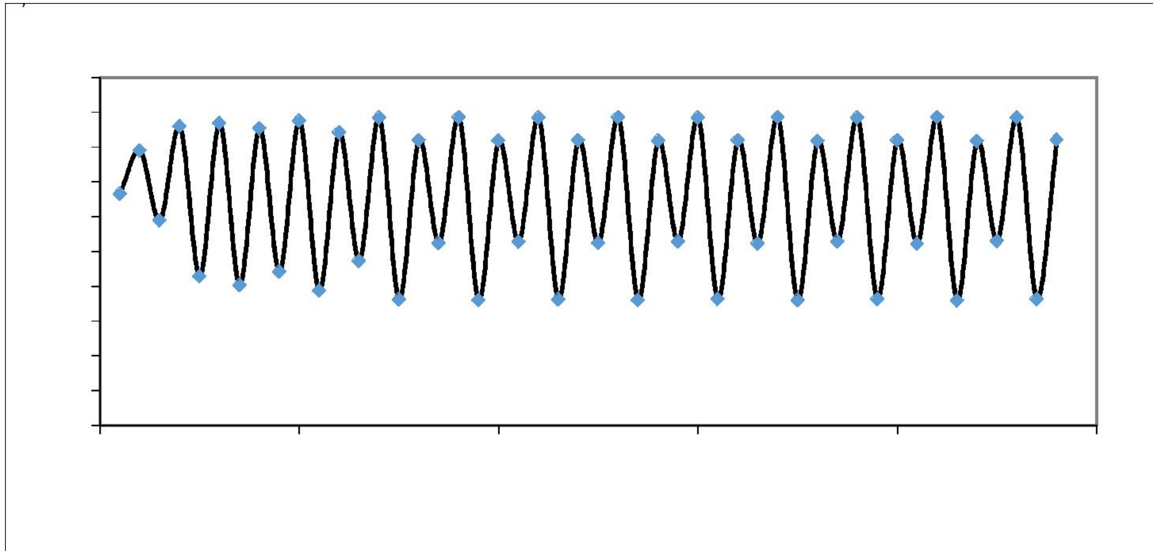
Logistic Map

- $x_{(t+1)} = ax_t(1 - x_t)$, if $4 > a > 0$.
- If $1 < a < 3$, the outcome converges to $s = (a - 1)/a$, a fixed value;
  - a = 2,75, $x(0)$ = 0,75.



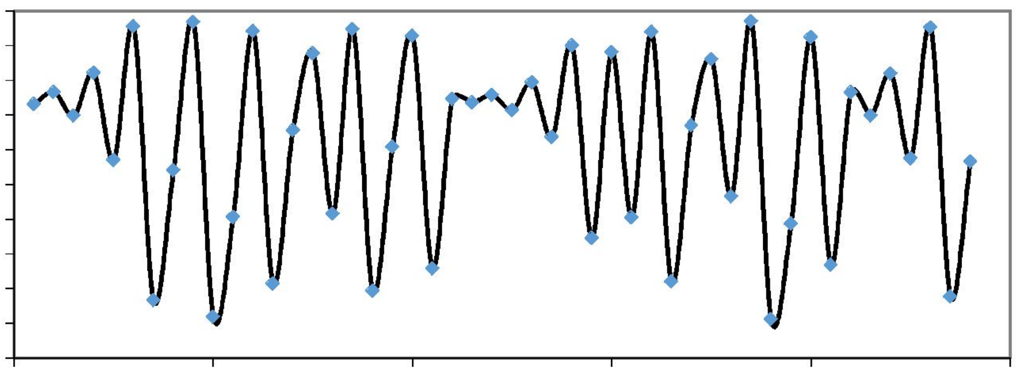
Logistic Map

- $x_{(t+1)} = ax_t(1 - x_t)$, if $4 > a > 0$.
- If $3 < a < 3.57$, the outcome becomes cyclic;
  - a = 3,55, x(0) = 0,75.



Logistic Map

- $x_{(t+1)} = ax_t(1 - x_t)$, if $4 > a > 0$.
- If $a > 3.57$, the outcome bifurcates, it is the chaos edge;
  - a = 3,9, $x(0)$ = 0,75.



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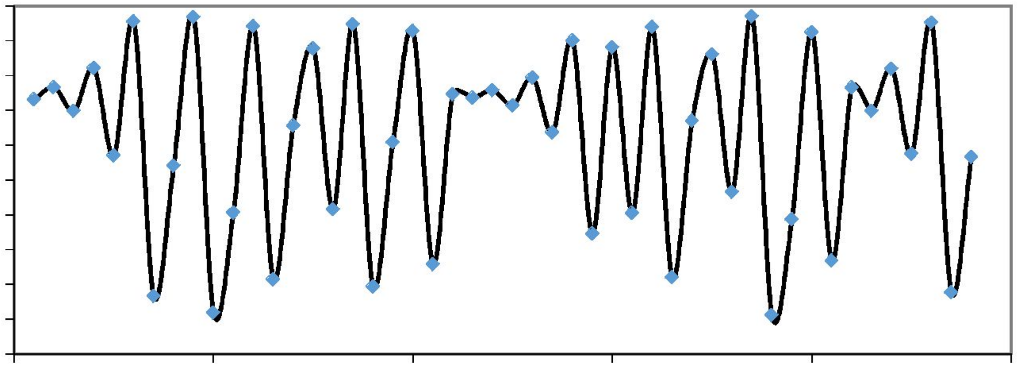
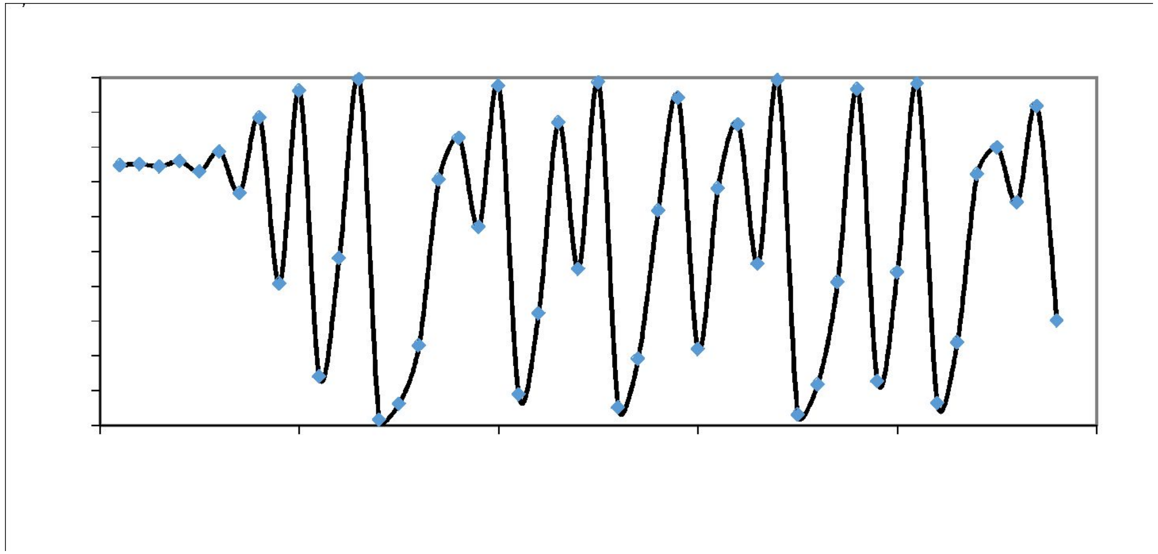
Logistic Map

- $x_{(t+1)} = ax_t(1 - x_t)$, if $4 > a > 0$.
- If $a > 3.57$, the outcome bifurcates, it is the chaos edge;
  - a = 3,9, s(0) = 0,75.



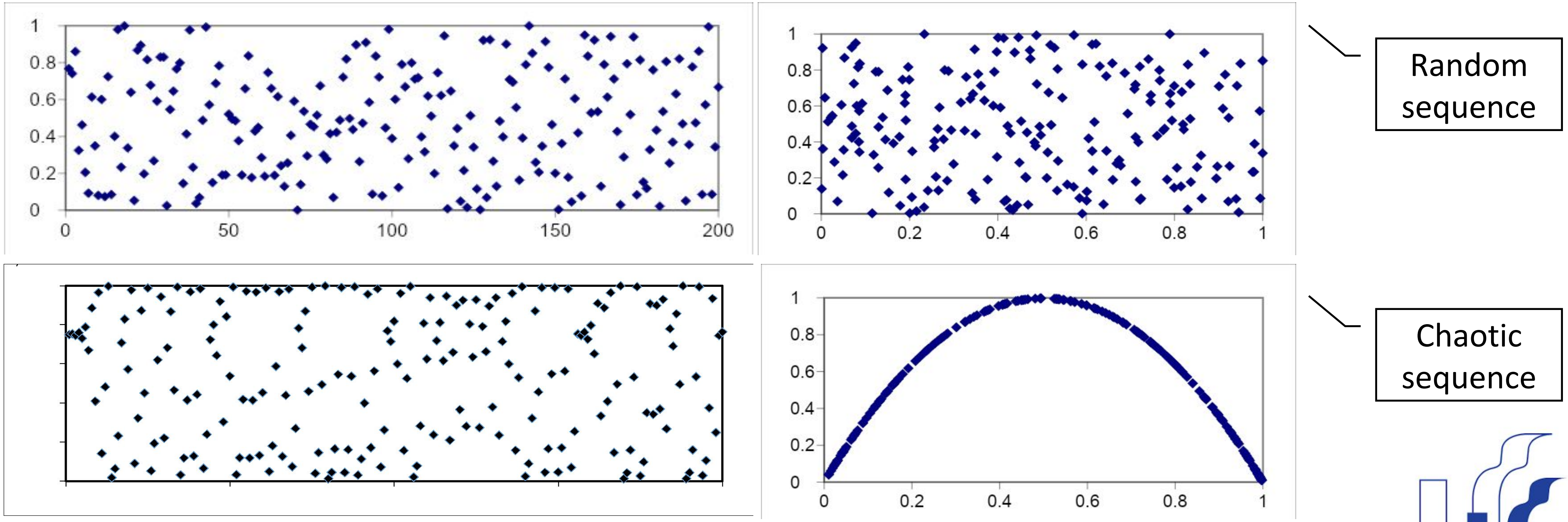
Logistic Map

- $x_{(t+1)} = ax_t(1 - x_t)$, if $4 > a > 0$.
- If $a > 3.57$, the outcome bifurcates, it is the chaos edge;
    - a = 3,99, $x(0)$ = 0,75.



Logistic Map

- In the chaos edge, the outcome seems to be random, but it is not;
- Plotting $[x_{(t+1);} x_t]$, a regular pattern arises, reinforcing the notion of deterministic chaos.



Information Theory

- Information is the opposite of uncertainty;
- The greater the uncertainty a message dissipates, the more information the message contains;
- Therefore, the more unlikely the content of the message, the greater the chance it eliminates and the greater the amount of information it contains;
  - “Man who bites a dog” and “airplane that crashes” have more information than “dog that bites a man and “airplane that completes the trip”;
- In the manufacturing, it is more important for informational intelligence to save, recover, and dispose of failure data than normal operation data.

Information Quantity

- Try to guess the right word (not a possible word, but the exact word, i.e. the missing letter):
  - B_EF;
  - SIN_;
- The easiest word is the one in which the least amount of information is missing;
- For *p* possible messages, with probability distribution *P*(*s*), the average information content in the source is given by the so-called Shannon entropy.

$$\bar{I} = -\sum_{i=1}^{p} P(s_i).\log[P(s_i)]$$

Information Quantity

- B<u>**E**</u>EF;
  - If *p* = 2 and the probabilities are [E = 99%, other = 1%], than the missing information quantity is:
  - *I* = -[0,9 * log(0,9) + 0,1 * log(0,1)] = 0,08 bits (almost nothing new);
- SIN<u>**K**</u> or SIN<u>**G**</u> or SIN<u>**C**</u> or SIN<u>**S**</u>;
  - If *p* = 4 and the probabilities are [A = E = I = O = 25%], than the missing information quantity is :
  - *I* = -[4 * (0,25 * log(0,25)] = 2 bits;
- As the odds in the second word are greater, the second missing letter dissipates more uncertainty and the amount of information is greater than the first.

Supply Chains, Networks, Ecosystems, Tecnosystems, Industrial Districts, Short Supply Chains: strategy and complexity

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Networks: complexity

- Networks appear when several companies, spontaneously or not, cooperate to achieve priorities, or individually take advantage of fractors due to the existence of the network;
- It is not possible to explain a network by explaining only the relationships between the parts, two by two; it is necessary to explain relationships between all parts;
- Every part affects and is affected by every other part, and as the network grows, the number of relationships grows more than linearly.

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Primitive meta-strategies in networks

- **Efficiency**: stable environment, defined and regular demand, little innovation; focus on smooth, continuous flows;
  - competition priorities: low price, on-time delivery, conforming quality;
- **Responsivity**: unstable environment, uncertain demand, major innovation; focus on fast and discontinuous flows;
  - competition priorities: ability to change the product (flexibility), innovation.

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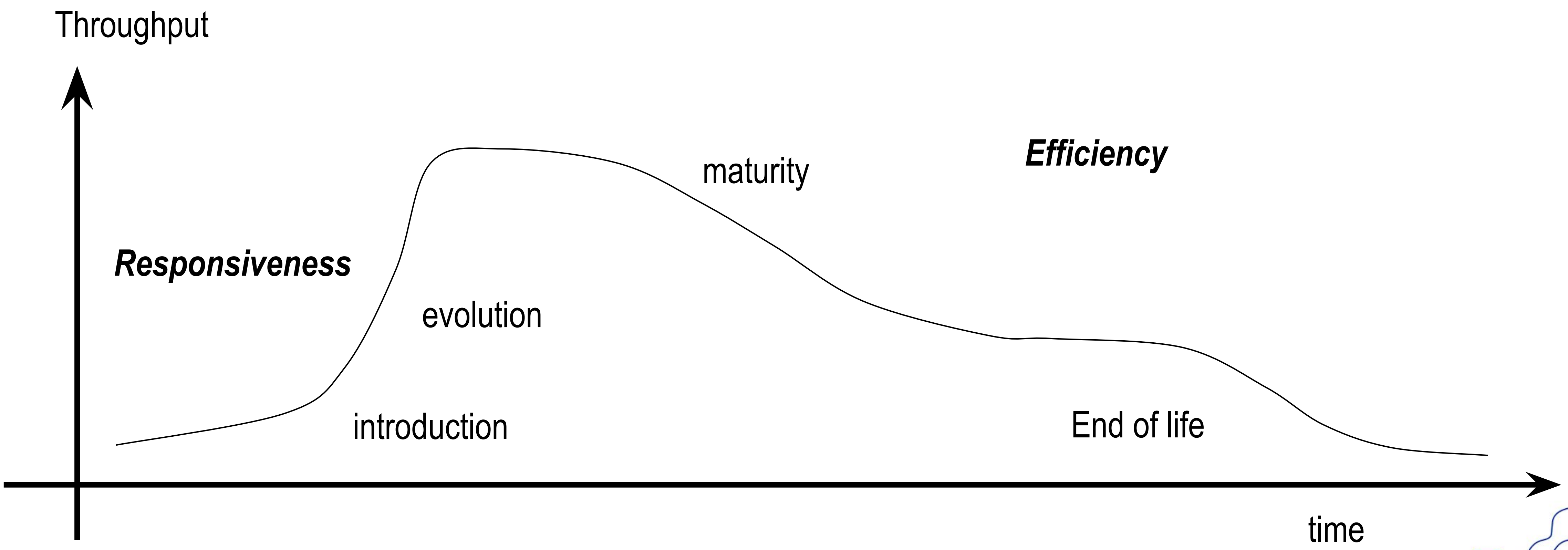
Matching Life Cycle and Strategy



Complex Methods in Networks

- In the early days of industrialization, artisanal manufacturing was complex, as it depended on combinations of factors, such as machines, materials, product design, and mainly operator skills;
- Rationalization and management methods, particularly interchangeability of parts and automation, have consistently reduced the complexity;
- Recently, the need to achieve multiple strategic objectives at the same time (cost, quality, flexibility, delivery) has again increased the complexity of manufacturing.

Complex Methods in Networks

- To manage the complexity, it is necessary to measure and modify it accordingly, there is, to measure and modify the amount of information needed to run the strategy;
- A stable and functional, efficient SC generates few anomalies and needs little information, which implies low complexity
- An unstable and innovative, responsive SC, requires handling new situations to handle, which implies high complexity.

Shannon´s Entropy: *H*(*p*)

- If *k* different pieces of information are needed to manage uncertainties from *m* sources, the amount of entropy in the network is :

$$H(network) = -\sum_{j=1}^{m}\sum_{i=1}^{k}[p_i.\log(p_i) + (1-pi).\log(1-p_i)]$$

- If *n* = 2 (information required *ii* = 1, otherwise *ii* = 0):

$$H(network) = -\sum_{j=1}^{m}\sum_{i=1}^{k}\sum_{ii=1}^{2} p_i.\log_2(p_i); \qquad [p1 + p2] = 1$$

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Framework: information needed to manage uncertainties in the footwear industry (empirically collected)

Issue	Tag	Information
Planning and	I1	Forecasting
scheduling	I2	Manufacturing capacity
	I3	Scheduled maintenance
	I4	Lead-times and deadlines
Logistics	I5	Scheduled shipments
	I6	Scheduled arrivals
	I7	Shared inventory situation
	I8	Shared transportation situation
Labor	I9	Availability of skilled operators
	I10	Availability of skilled designers
Finance	I11	Cash-Flow
	I12	Shared purchases
	I13	Credit, payments, and loans
	I14	Shared Financing
Technology	I15	Product development
and	I16	Process development
innovation	I17	Shared investments
	I18	Shared machine
	I19	Technology transfer
	I20	Technical support

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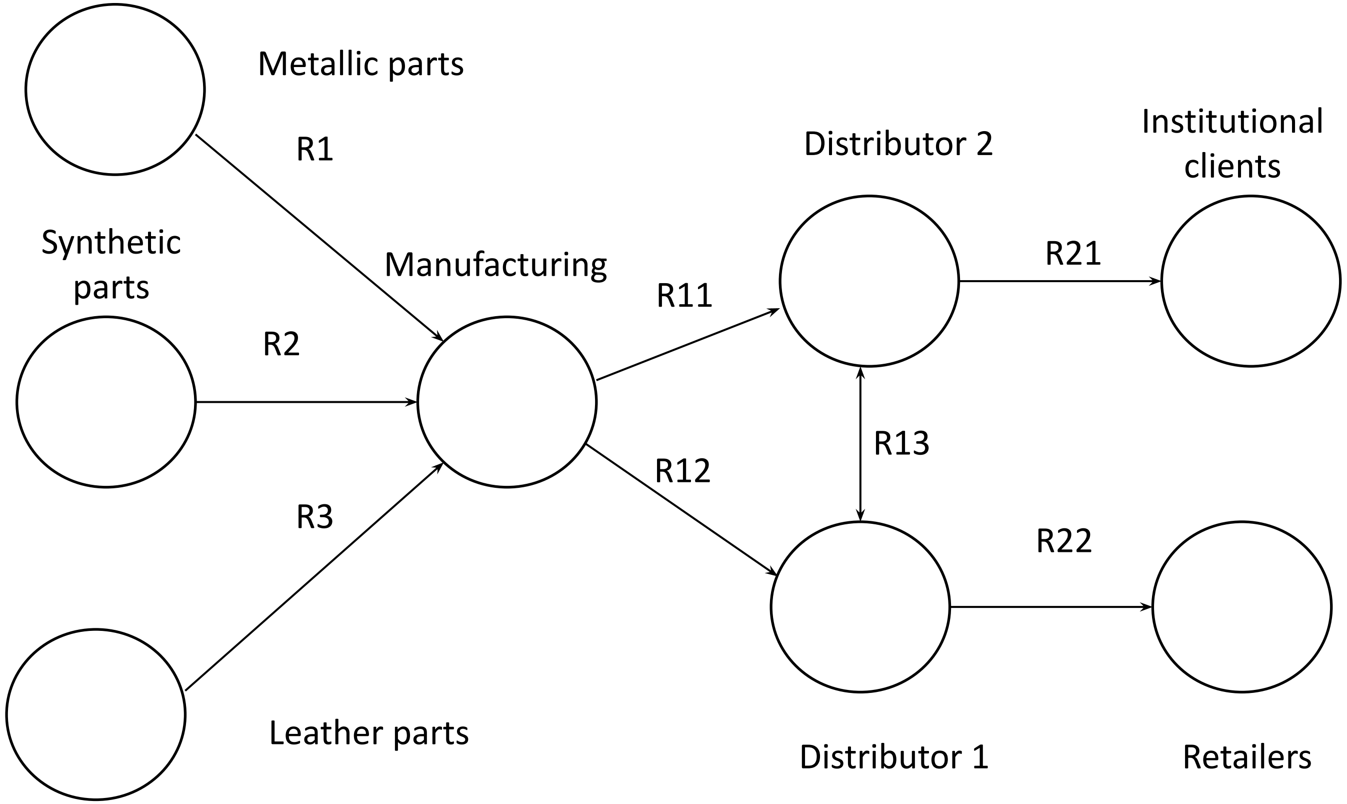
Application 1, efficiency: safety shoes

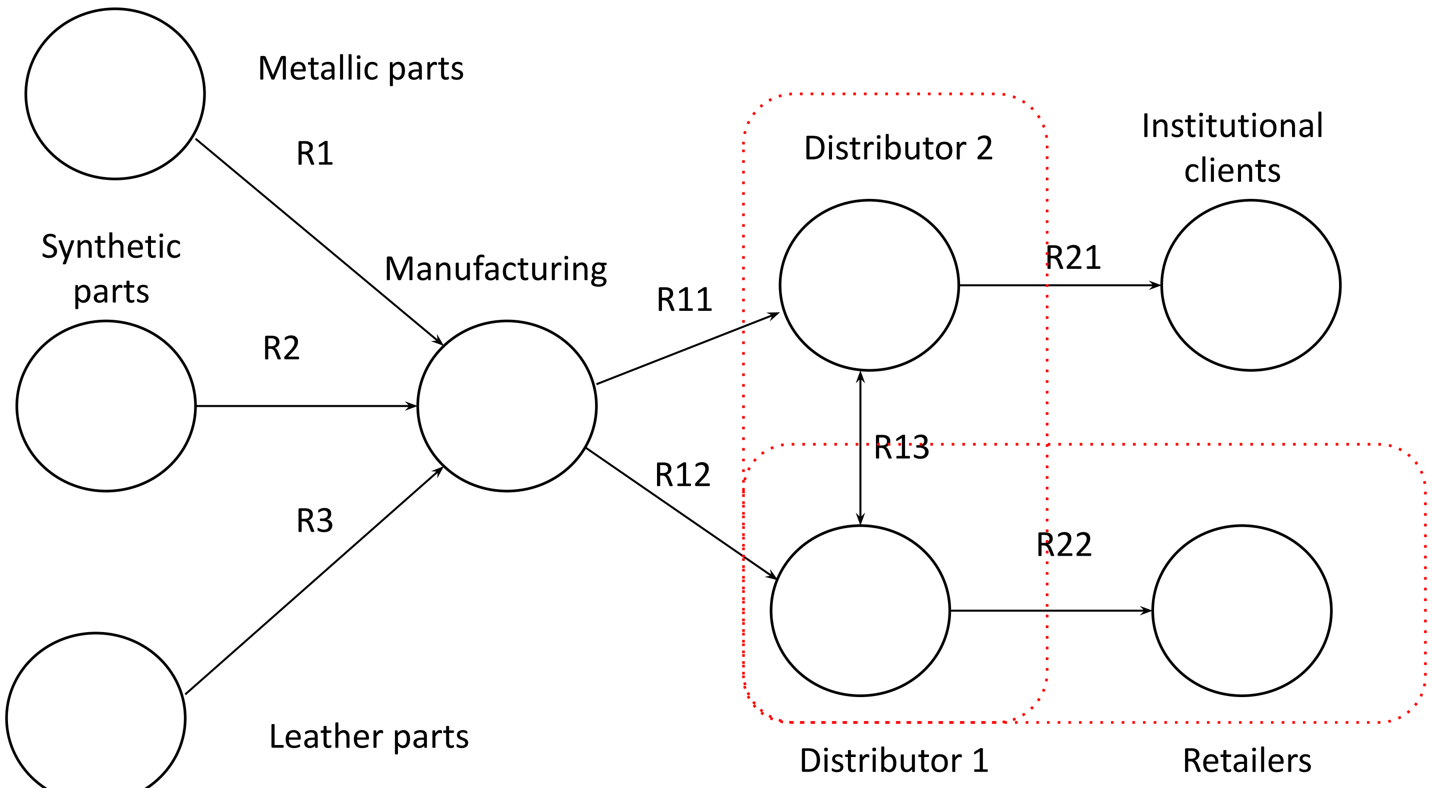


Application 1, efficiency: safety shoes

	R1	R2	R3	R11	R12	R13	R21	R22
I1							10%	50%
I2	30%	60%						
I3	50%		60%					
I4							30%	60%
I5								
I6								
I7						10%		
I8						10%		
I9								
I10	10%							
I11	20%	10%	40%				10%	50%
I12						30%		
I13	50%	20%	50%			30%		
I14						20%		
I15	10%	20%						
I16	40%	60%						
I17						10%		
I18								
I19	20%							
I20	20%	40%				10%	10%	

- $H(network) = -\sum_{j=1}^{8}\sum_{i=1}^{20}\sum_{i=1}^{2} p_i . \log_2(p_i) = 24.34\ bits$
- Such an absolute number says almost nothing, as it depends on the size and extent of the network;
- Taking $\frac{d}{dp}H(p) = 0$, $H(p)$ passes for a maximum at $p = 0.5$;
- The maximum possible complexity is $H(0.5) = 160$ bits and the relative complexity, which is comparable, is 24.34/ 160 = 15.2%.

Application 1, efficiency: safety shoes



Complexity sources:

- Redundant channels; and
- Dependability for local deliveries.

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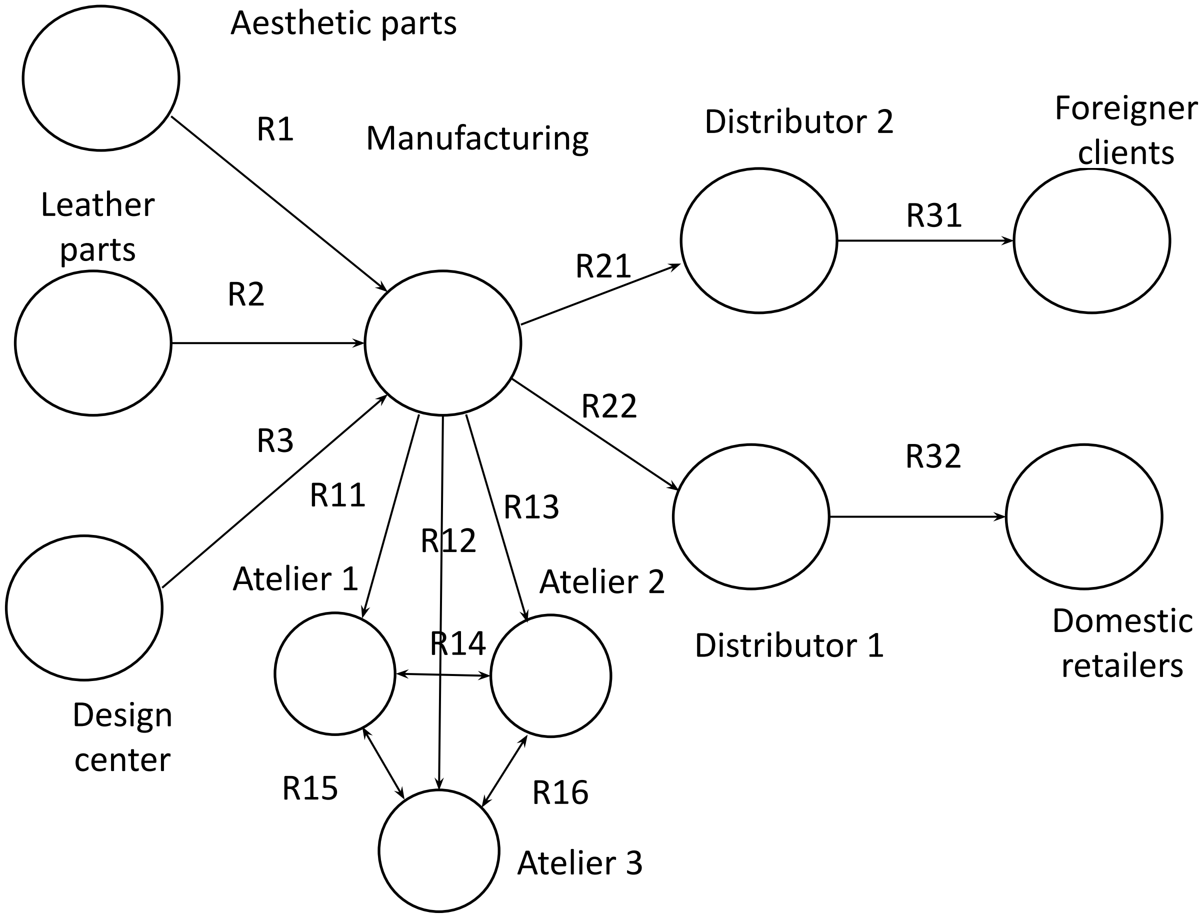
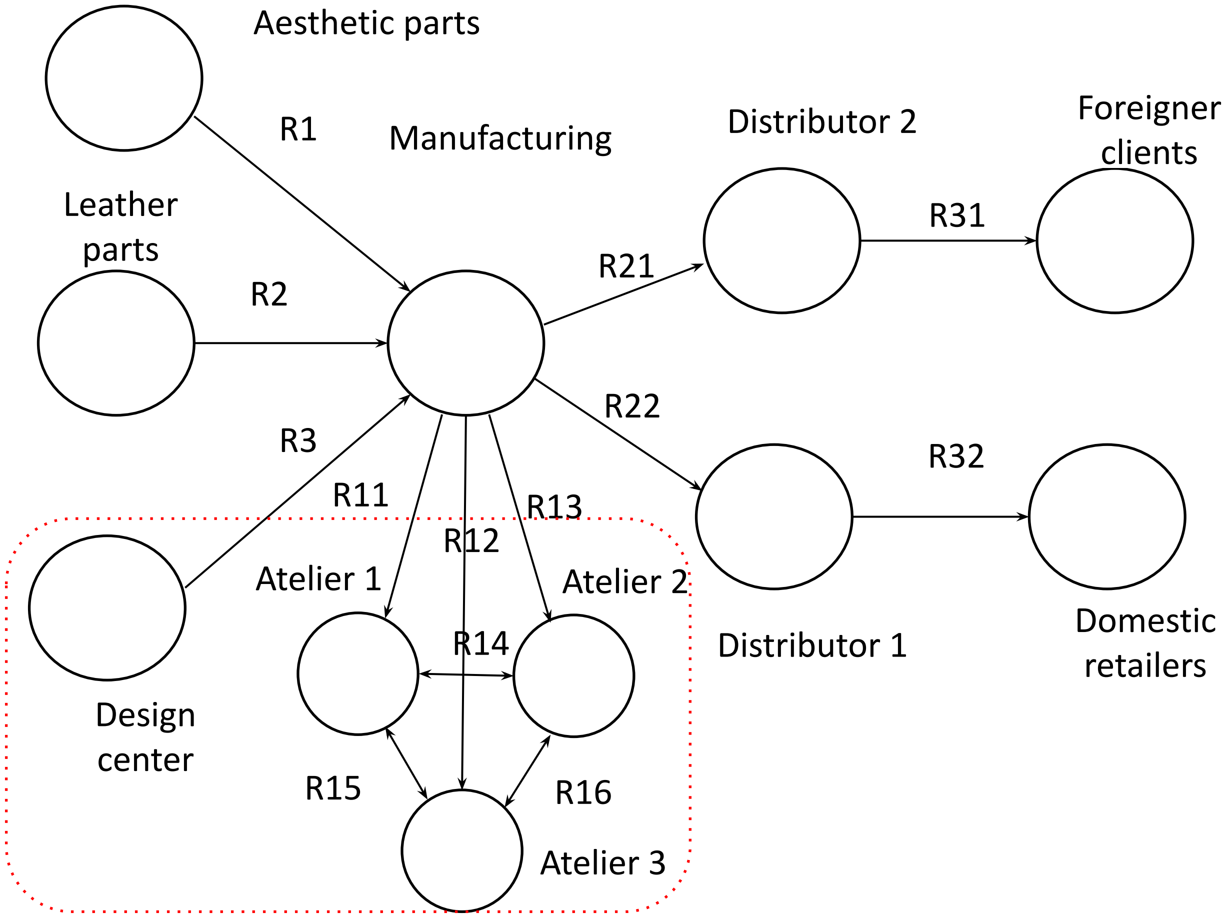
Application 2, responsivity: luxury shoes



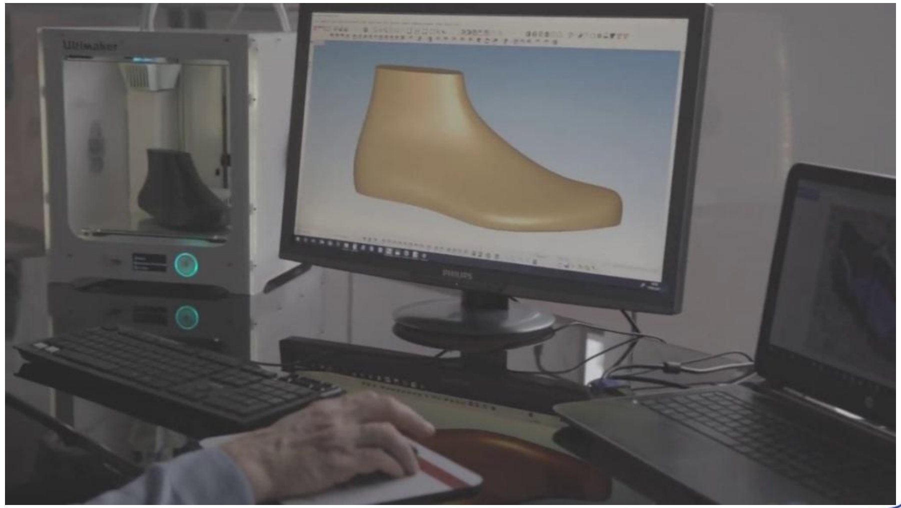
- $H(network) = 72.87\ bits$
- Relative complexity= 72.87/ 260 = 28.0%.

Application 2, responsivity: luxury shoes



Complexity sources:

- innovation; and
- flexibility.



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Comparison

Competitive dimension	Importance N1	Importance N2
Cost	High	Low
Quality	High	Low
Dependability	Intermediate (*)	Intermediate
Flexibility	Low	High (*)
Innovation	Low	High (*)
Relative Complexity	15%	28%

Source of complexity (*)

Complexity and Performance

- Initial studies by GEEP (PPGEPS UNISINOS) and DISMI (UNIMORE) indicate strong non-linearity in the relationship between complexity and performance in manufacturing networks;
- They also indicate that such non-linear relationships depend on the competitive priority that the network chooses.

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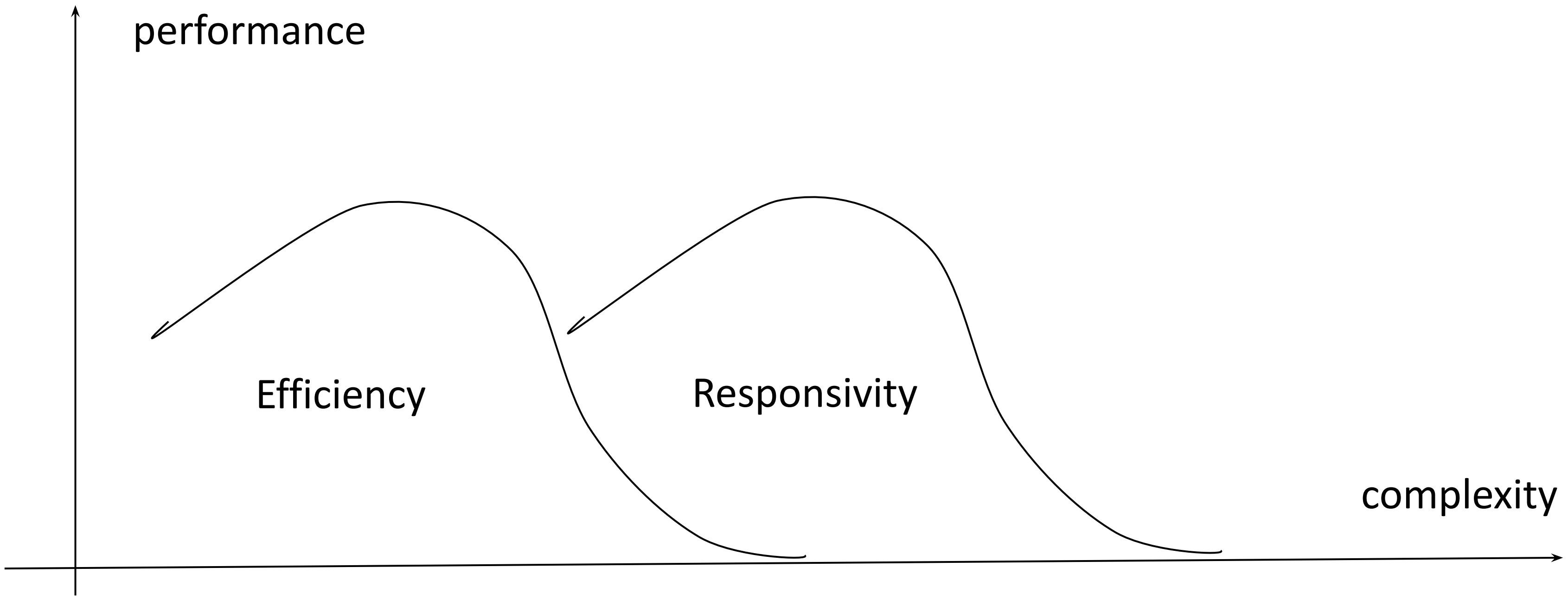
Complexity and Performance

- A proposition to verify in further studies.



Post-pandemic scenario

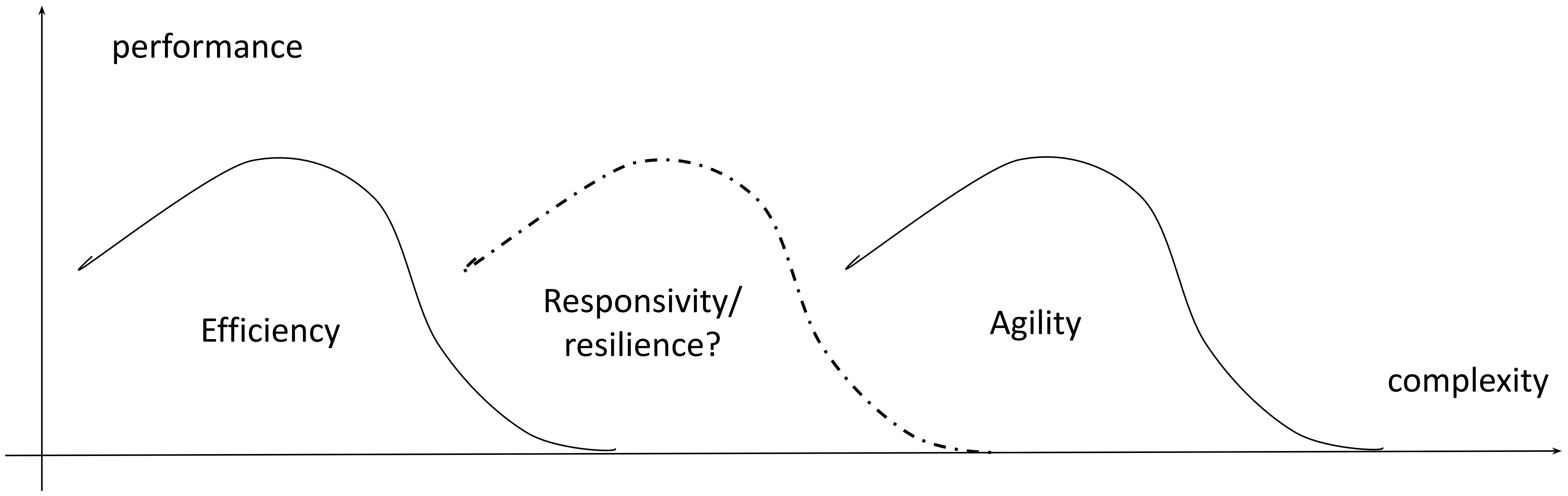
- In pandemic times, industry has been severely affected by disruptions in supply chains;
- A new source of complexity arises, how global supply chains should deal with disruption risk;
- Two new strategic scenarios that were already proposed in SC strategic studies seems to enhance relevance: agility (not only responsivity), and resilience (not only efficiency).

Post-pandemic scenario

Supply uncertainty	Demand uncertainty: low (functional product)	Demand uncertainty: high (innovative product)
low (stable process)	Efficiency	Responsivity
high (unstable process)	Resilience	Agility

Complexity and Performance: the next step

- How should such a relationship be?



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Some initial publications

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Spare Parts Replacement Policy Based on Chaotic Models

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sellitto@unisinos.br