POLITECNICO DI MILANO

Knowledge Aided Engineering Manufacturing and Related Technologies

Network of Evolutionary Trends and maturity assessment through contradictions analysis

Niccolò Becattini

Gaetano Cascini - gaetano.cascini@polimi.it

Federico Rotini

Context

- Nowadays the **analysis of emerging technologies** and their potential impact on markets, economies and societies requires **reliable and repeatable methods and tools** since the related information plays a critical role for strategic decisions of private and public organizations
- Not surprisingly, more than **fifty methodologies** with different characteristics and specific purposes have been proposed so far in this field [1]
- ☹ Nevertheless all these techniques reveal **several weaknesses** [2] as: **limited accuracy** on middle and long-term forecast; **poor repeatability**; poor adaptability, i.e. no universal methods are known, besides complementary instruments must be integrated according to the specific goal and data availability.

[1] Porter, A.L. et al.: "Technology Future Analysis: Toward integration of the field and new methods". Technological Forecasting & Social Change 71, pp. 287–303, 2004.

[2] Kucharavy, D. and De Guio, R.: "Problems of Forecast". Proceedings of the 5th ETRIA TRIZ Future Conference, ISBN 3-7011-0057-8, Graz, Austria, November 16-18, 2005.

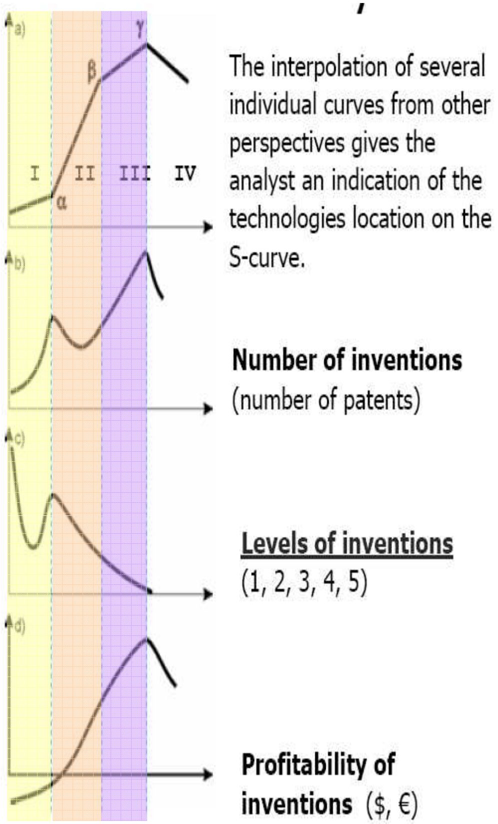
Context

- TRIZ is emerging as a systematic forecasting methodology and the TRIZ community widely claims the benefits arising from the application of Altshuller's **Laws of Engineering System Evolution (LESE)**

☹ Nevertheless, while these tools reveal relevant potentialities in several specific situations, **their integrated use is limited to inventive problem solving tasks (ARIZ), while it is still missing for forecasting applications.**

Context

- The assessment of the maturity level of a technology is an even tougher task. According to classical TRIZ, **Technology Maturity Assessment** can be done through the curves of system development, number of inventions, level of inventiveness and profitability.
- ☹ Besides, these curves are **hardly usable for practical scopes**, despite what has been claimed in several publications like [3-5], also due to the lack of information about the way Altshuller himself built them (therefore, with no references about their limits of validity).



* G.S.Altshuller: 1979. CREATIVITY AS AN EXACT SCIENCE. Sovietskoe radio, Moscow.

[3] Mann D.: "Using S-Curves and Trends of Evolution in R&D Strategy Planning", the TRIZ Journal, July, 1999.

[4] Gibson N., Slocum M.S., Clapp T.G.: "The Determination of the Technological Maturity of Ultrasonic Welding", the TRIZ Journal, July, 1999.

[5] Gahide S., Clapp T.G., Slocum M.S.: "Application of TRIZ to Technology Forecasting - Case Study: Yarn Spinning Technology", the TRIZ Journal, July, 2000.

Goal and outline

- **Step-by-step algorithm** for analyzing a Technical System (TS) and the way its Main useful Function (MUF) is delivered at different detail levels
  - The working principle is then compared with previous generations of the system in order to build a **structured classification of the information for evolutionary comparisons**
  - These comparisons allow to build a **network of scenarios** with different involvement of resources, which constitutes a map of the TS evolution, where already commercialized products are visualized together with emerging patented inventions and free spaces for investments
  - Correlate the **maturity of a technology** with the evolution of the contradictions underlying its application in a certain field
  - The choice of the **favorite strategical direction** is still assigned to the beneficiaries of the forecast according to their attitude to the world, their mission and values, as already suggested by Altshuller

Goal and outline

- **Step-by-step algorithm** for analyzing a Technical System (TS) and the way its Main useful Function (MUF) is delivered at different detail levels

- Outline
  - Related Art
  - Reference models for system analysis
  - Functional modeling for TRIZ-based evolutionary analyses
  - Building a **Network of Trends (NET)**
  - **Correlation between Contradictions and Evolutionary Stages**
  - Exemplary application
    - Production of tablets in the pharmaceutical manufacturing sector
  - Conclusions and future works

Related art: TRIZ instruments and forecasting

- Fey and Rivin [6]: TRIZ as a “powerful structured methodology for a directed development of new products/processes”
  Methodological description limited to the LESE with a number of examples ➔ no details about the way the TRIZ laws should be applied
- Cavallucci [7]: integration of TRIZ LESE into the product development cycle as a means to predict the impact of a technical solution

☹ **No directions** are provided to identify elements and functions to be evaluated and further developed according to the LESE

☹ No specific comparison means are available

[6] Fey V. R., Rivin E. I.: “Guided Technology Evolution (TRIZ Technology Forecasting)”. The TRIZ Journal, January 1999, available at http://www.triz-journal.com/archives/1999/01/c/index.htm.

[7] Cavallucci, D.: “Integrating Altshuller's development laws for technical systems into the design process”. CIRP Annals - Manufacturing Technology, vol. 50(1), 2001, pp. 115-120.

Related art: TRIZ instruments and forecasting

- A few TRIZ professionals have proposed integrated procedures for technology forecasting purposes [8, 9]

☹ Both Directed Evolution by Zlotin, Zusman and Evolution Trees by Shpakovsky are still **mostly focused on the interpretation of the LESE** than on the analysis of the system the forecast is about

☹ **The lack of preliminary classification is the main reason for poor repeatability of TRIZ forecasts,** since different researchers apply TRIZ LESE to different details/characteristics of the same technical system and/or limit their study to superficial features of the system itself

[8] Zlotin, B.L. and Zusman, A.V.: "Directed Evolution. Philosophy, Theory and Practice". Ideation International Inc. ISBN 192874706X, 2001.

[9] Shpakovsky N.: "Evolution Trees. Analysis of technical information and generation of new ideas" (in Russian), ISBN 5-9348-6048-8, TRIZ Profi, 2006.

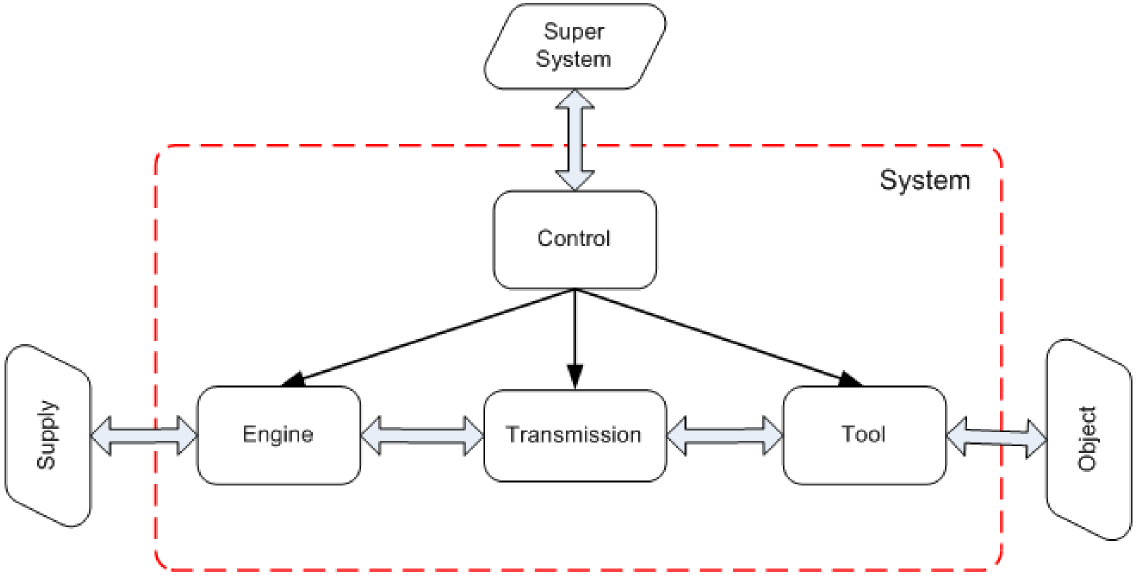
Reference models for system analysis

- **EMS model** [10]: Any technical system can be modeled as a black box channeling or converting energy, material and or signals (information) to achieve a desired outcome

[10] Pahl, G. and Beitz, W.: "Engineering Design. A Systematic Approach", 2nd edition, Springer, ISBN:3540199179, 544 pp., 1996.

Reference models for system analysis

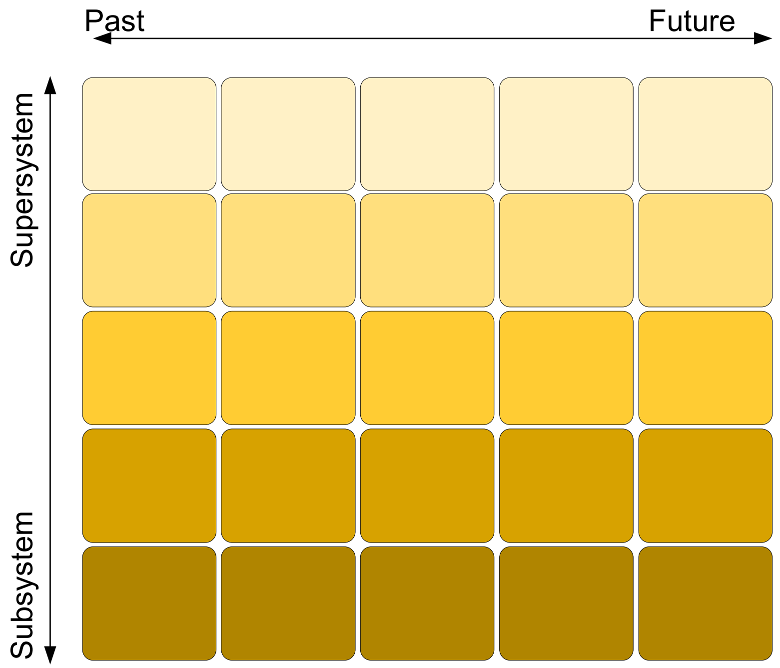
- **Minimal Technical System** [11]: whatever is the complexity of the system to be analyzed, four elements must be recognized: a **Tool**, i.e. the working element delivering the function of the TS; a **Supply**, i.e. the element providing the energy necessary to produce the expected effect of the function; a **Transmission**, i.e. the element transmitting energy from the Supply to the Tool; a **Control**, i.e. an element governing at least one of the above elements.
  - According to the classical definition of the minimal technical system, just energy flows are taken into account; besides, the concept of the Law of Completeness of System Parts can be extended also to different types of flows, namely Material and Signals.

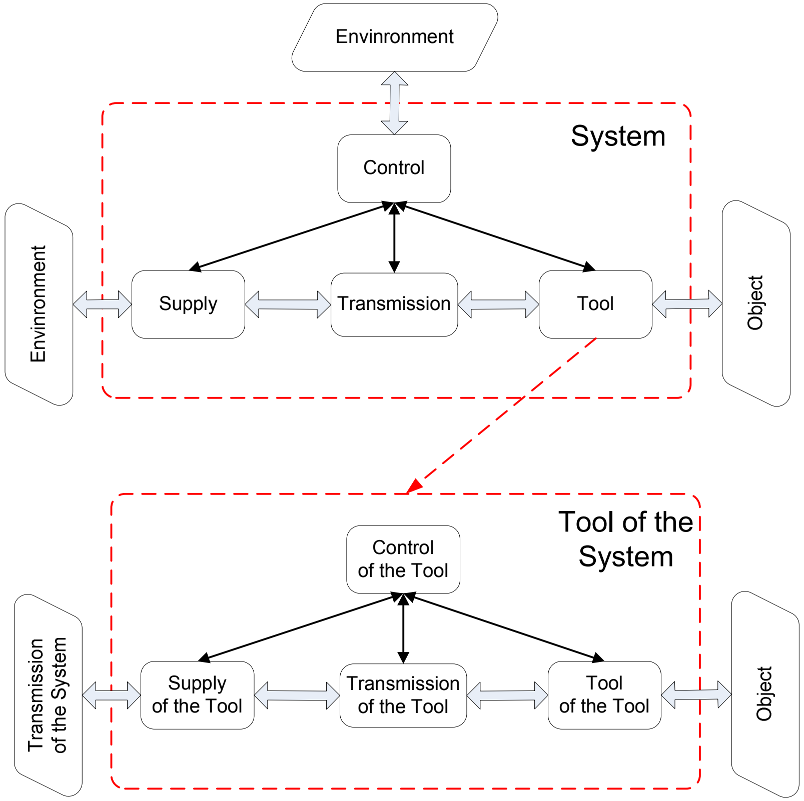


[11] Altshuller, G.S.: “Creativity as an Exact Science: The Theory of the Solution of Inventive Problems”. Gordon and Breach Science Publishers, ISBN 0-677-21230-5, 1984 (original publication in Russian - 1979)

Reference models for system analysis

- **System Operator** [11]: The analysis must be conducted at different detail levels with a proper hierarchical classification of system elements





[11] Altshuller, G.S.: "Creativity as an Exact Science: The Theory of the Solution of Inventive Problems". Gordon and Breach Science Publishers, ISBN 0-677-21230-5, 1984 (original publication in Russian - 1979)

Reference models for system analysis

- **Function-Behavior-Structure (FBS)** [12]:
  - The **Function** of a TS is the motivation for its existence;
  - at the **Structure** level, a TS is constituted by entities, attributes of these entities and relations among them;
  - the **Behavior**, defined as sequential changes of objects state governed by the Laws of Nature, is the link between Function and Structure.

  - Different Behaviors can produce the same Function
  - Different Structures can be characterized by the same Behavior

[12] Gero, J.S. and Rosenman, M.A.: “A conceptual framework for knowledge based design research at Sydney University’s Design Computing Unit”. Artificial Intelligence in Engineering, Vol. 5(2), 1990, pp. 65-77

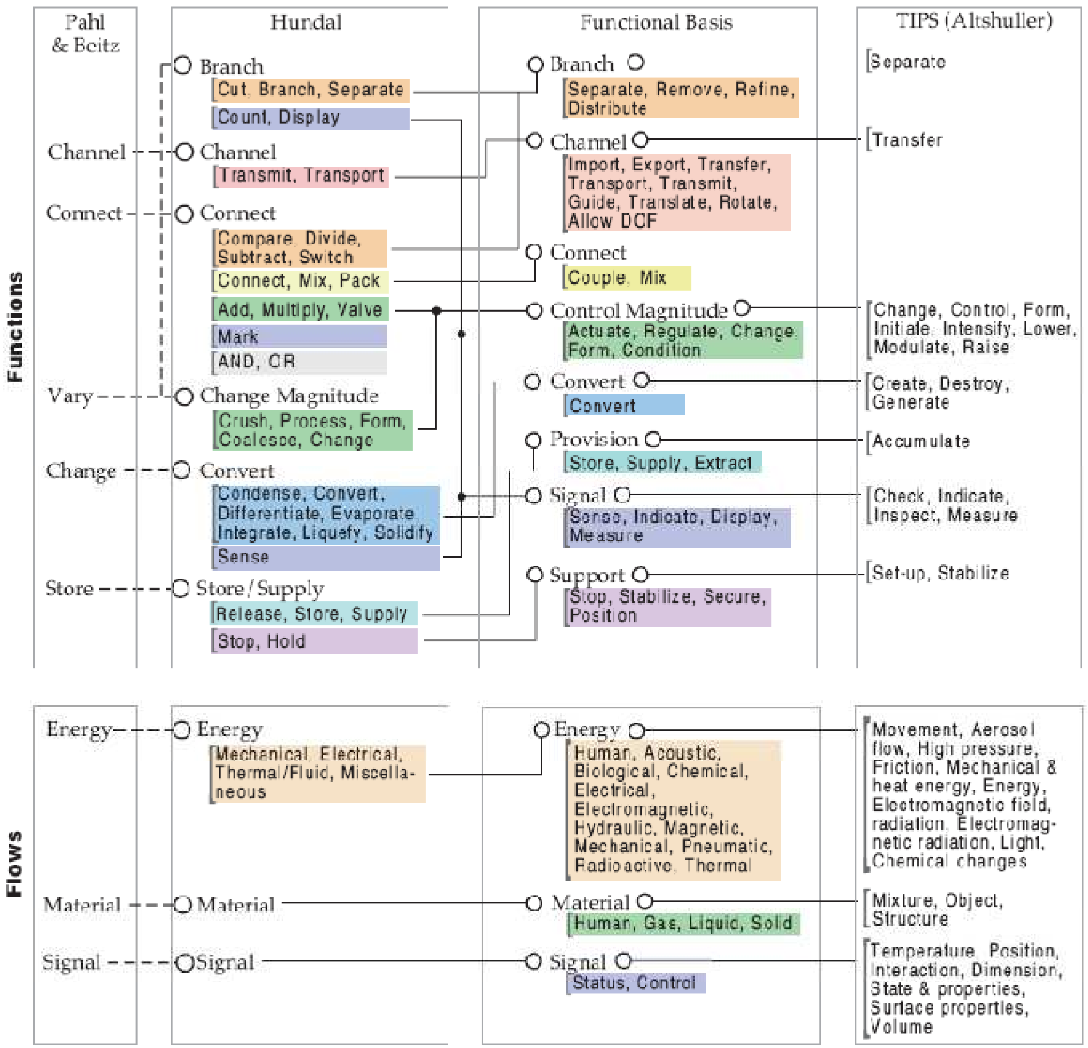
Reference models for system analysis

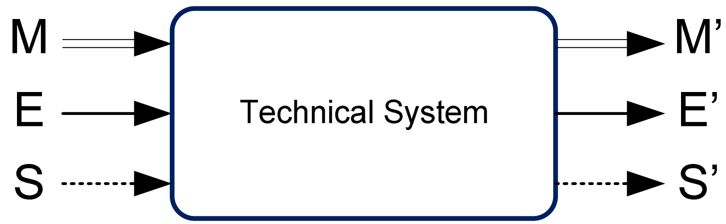
- **Functional Basis for Engineering Design** [13]: A formalized representations in function-based design
  - critical importance to reduce ambiguity at the modeling level (when multiple terms are used to mean the same things, or when the same term is used with multiple meanings)
  - improve repeatability of the models (the larger the number of terms there are in a vocabulary, the more different ways there are to model or describe a given design concept)

[13] Hirtz, J., Stone, R. B., McAdams, D. A., Szykman, S. and Wood, K. L.: "A Functional Basis for Engineering Design: Reconciling and Evolving Previous Efforts", NIST (National Institute of Standards and Technology) Technical Note 1447, February 2002.

Reference models for system analysis

Functional Basis for Engineering Design





Common base to define Flows and Action on the Flows

Reference models for system analysis

Functional Basis for Engineering Design

Class (Primary)	*Secondary*	*Tertiary*	*Correspondents*
Material	Human		Hand, foot, head
	Gas		Homogeneous
	Liquid		Incompressible, compressible, homogeneous,
	Solid	Object	Rigid-body, elastic-body, widget
		Particulate	
		Composite	
	Plasma		
	Mixture	Gas-gas	
		Liquid-liquid	
		Solid-solid	Aggregate
		Solid-Liquid	
		Liquid-Gas	
		Solid-Gas	
		Solid-Liquid-Gas	
		Colloidal	Aerosol
Signal	Status		
	Control		
Energy	Human		
	Acoustic		
	Biological		
	Chemical		
	Electrical		
	Electromagnetic		
	Hydraulic		
	Magnetic		
	Mechanical		
	Pneumatic		
	Radioactive/Nuclear		
	Thermal		

Overall increasing degree of specification →

Reference models for system analysis

Functional Basis for Engineering Design

Class (Primary)	*Secondary*	*Tertiary*	*Correspondents*
Branch	Separate		Isolate, sever, disjoin
		Divide	Detach, *isolate*, release, sort, split, disconnect, subtract
		Extract	Refine, filter, purify, percolate, strain, *clear*
		Remove	Cut, drill, lathe, polish, sand
	Distribute		Diffuse, dispel, disperse, dissipate, diverge, scatter
Channel	Import		Form entrance, *allow*, input, *capture*
	Export		Dispose, eject, *emit*, empty, *remove*, destroy, eliminate
	Transfer		Carry, deliver
		Transport	Advance, lift, move
		Transmit	Conduct, convey
	Guide		Direct, shift, steer, straighten, switch
		Translate	Move, relocate
		Rotate	Spin, turn
		Allow DOF	*Constrain*, unfasten, unlock
Connect	Couple		Associate, connect
		Joi	
		Lin	
	Mix		
Control Magnitude	Actuate		
	Regulate		
		Inc	
		De	
	Change		
		Inc	
		De	
		Sha	
		Co	
	Stop		
		Pr	
		Inh	
Convert	Convert		
Provision	Store		
		Co	
		Co	
	Supply		
Signal	Sense		
		De	
		Me	
	Indicate		
		Tr	
		Di	
	Process		
Support	Stabilize		
	Secure		
	Position		

Overall increasing degree of specification →

Class (Primary)	*Secondary*	*Tertiary*	*Correspondents*
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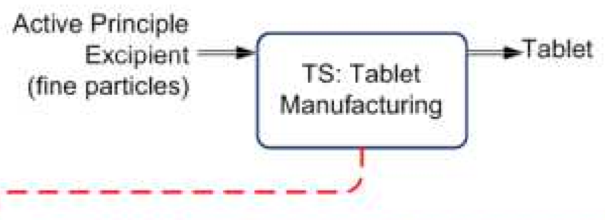
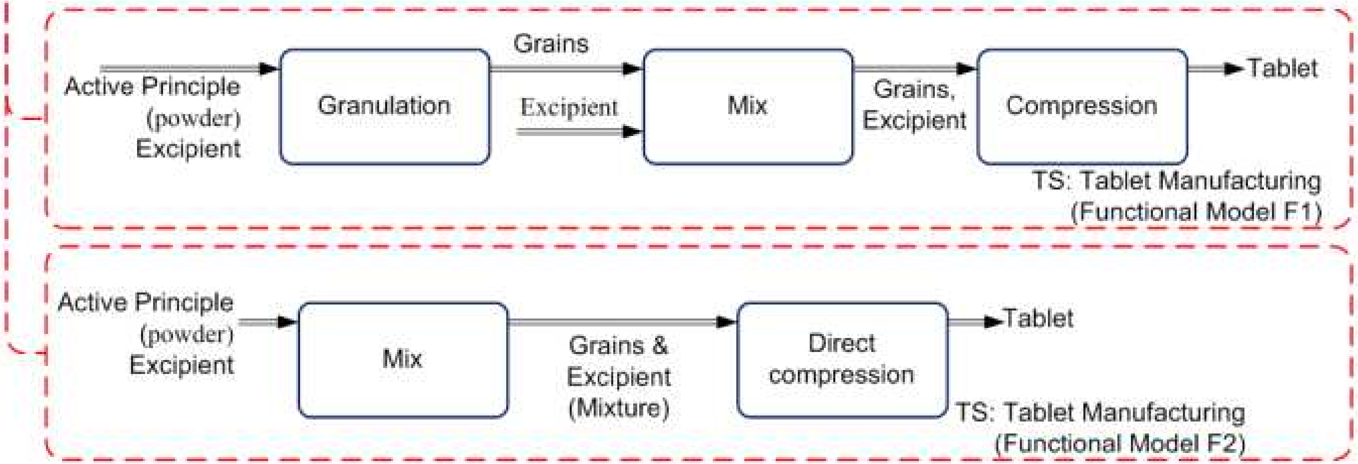
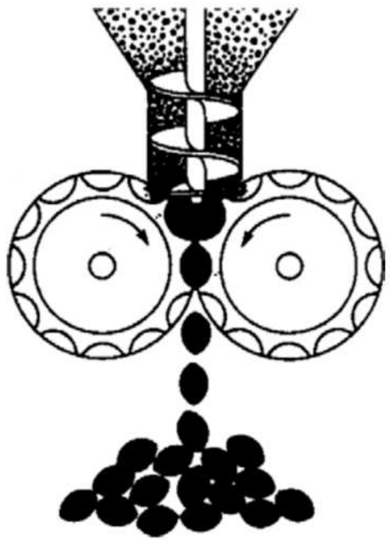
		Translate	Move, relocate
		Rotate	Spin, turn
		Allow DOF	*Constrain*, unfasten, unlock

Functional modeling for TRIZ-based evolutionary analyses

1. Describe the **function** of the system by means of the EMS model
   - ❖ Split the EMS model into elementary black boxes each delivering one of the basic actions constituting the NIST Functional Basis



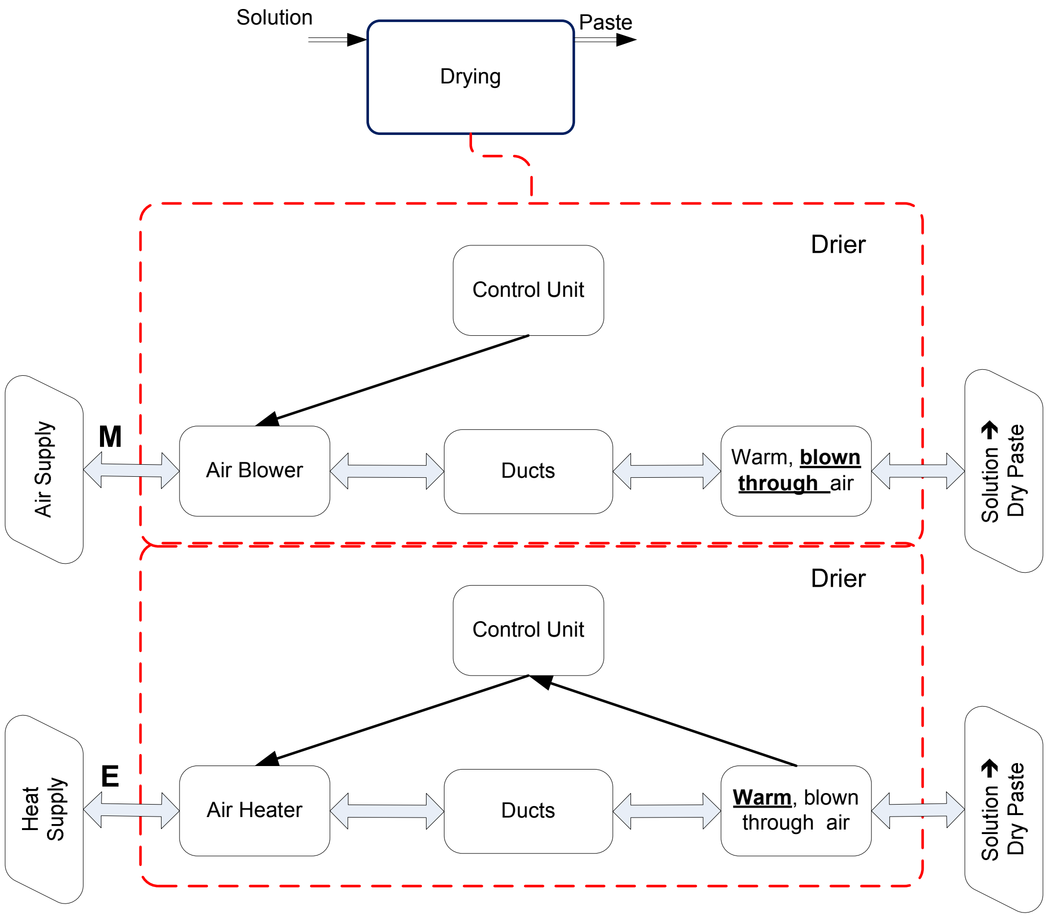




Functional modeling for TRIZ-based evolutionary analyses

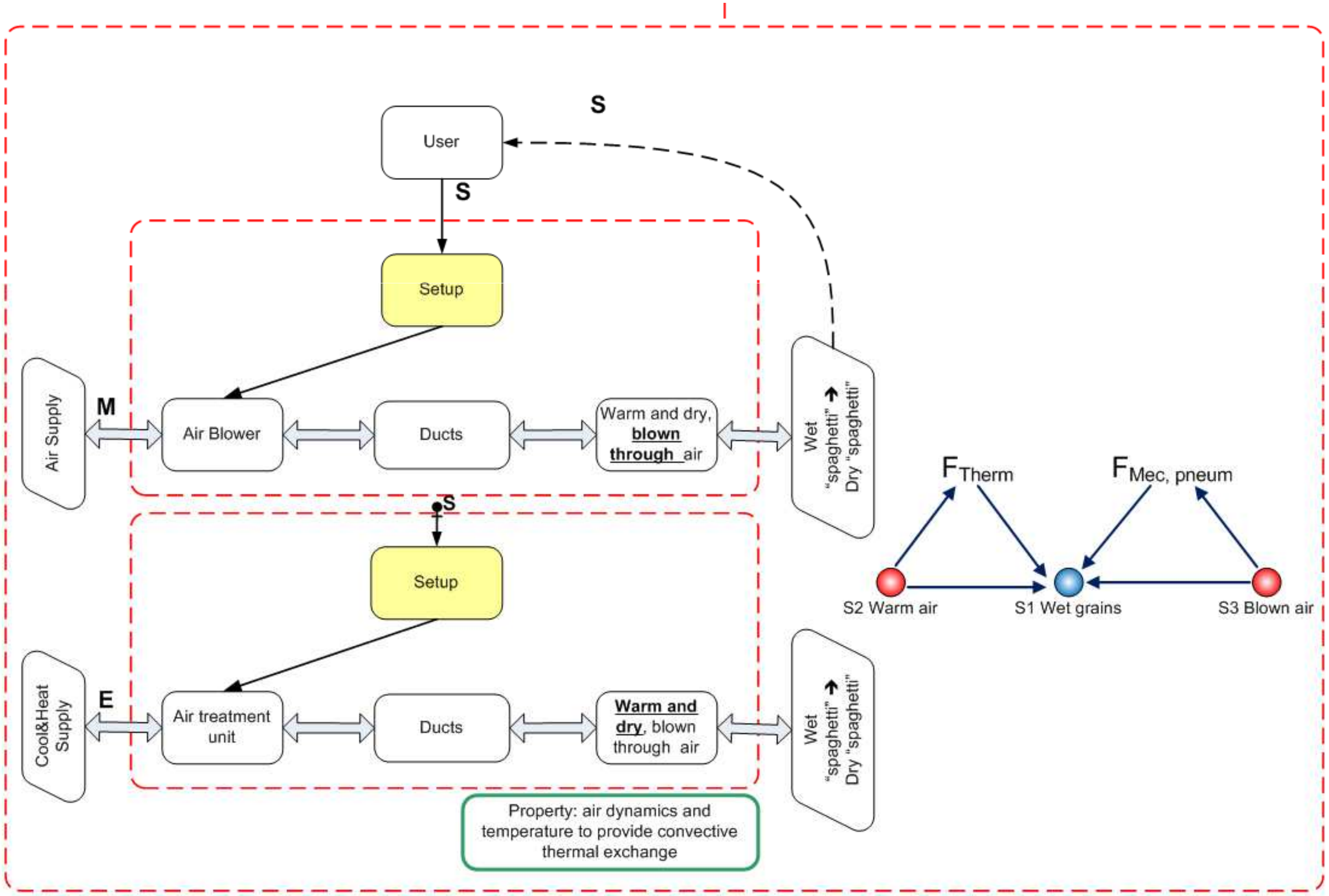
2. Describe the **behavior** of each elementary function by means of the Minimal Technical System model

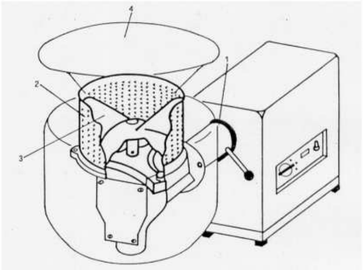
- identify the Product;
- identify the Tool, i.e. the element which acts directly on the Product;
- determine which properties characterize the Tool's capability to deliver the function to the Product;
- for each of the properties defined at previous step, identify the "Engine" from where the properties derives;
- complete the model of the minimal technical system, by adding the transmission from the Engine to the Tool, the control and its interactions with the other subsystems and the external supply of the engine.

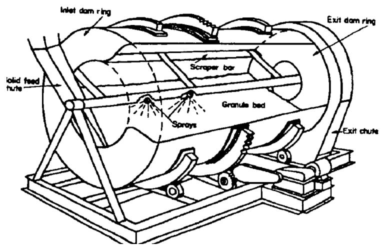


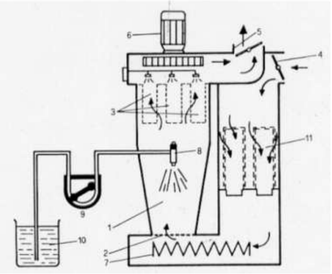
Functional modeling for TRIZ-based evolutionary analyses

3. Identify **Su-Fields interactions** for each interaction of the Minimal Technical System model



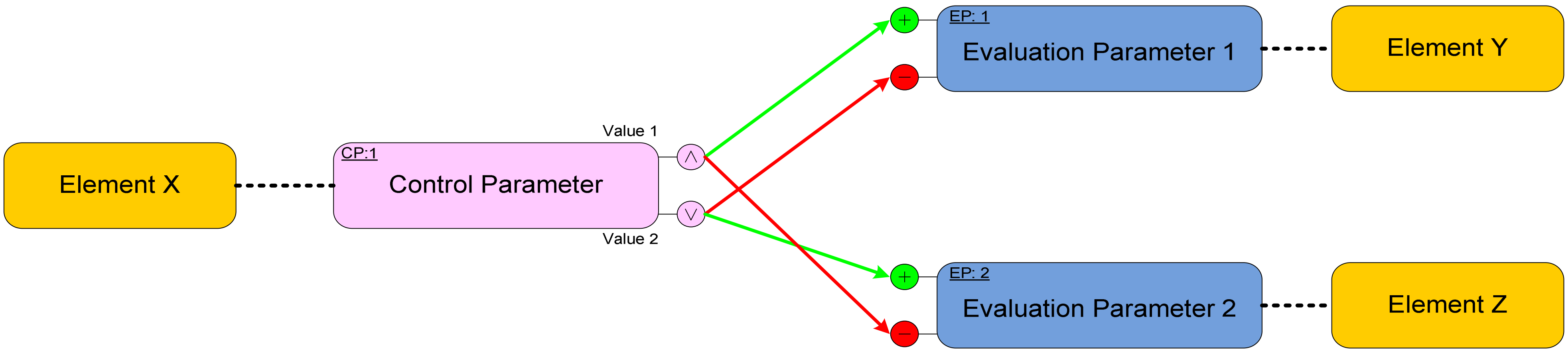






Functional modeling for TRIZ-based evolutionary analyses

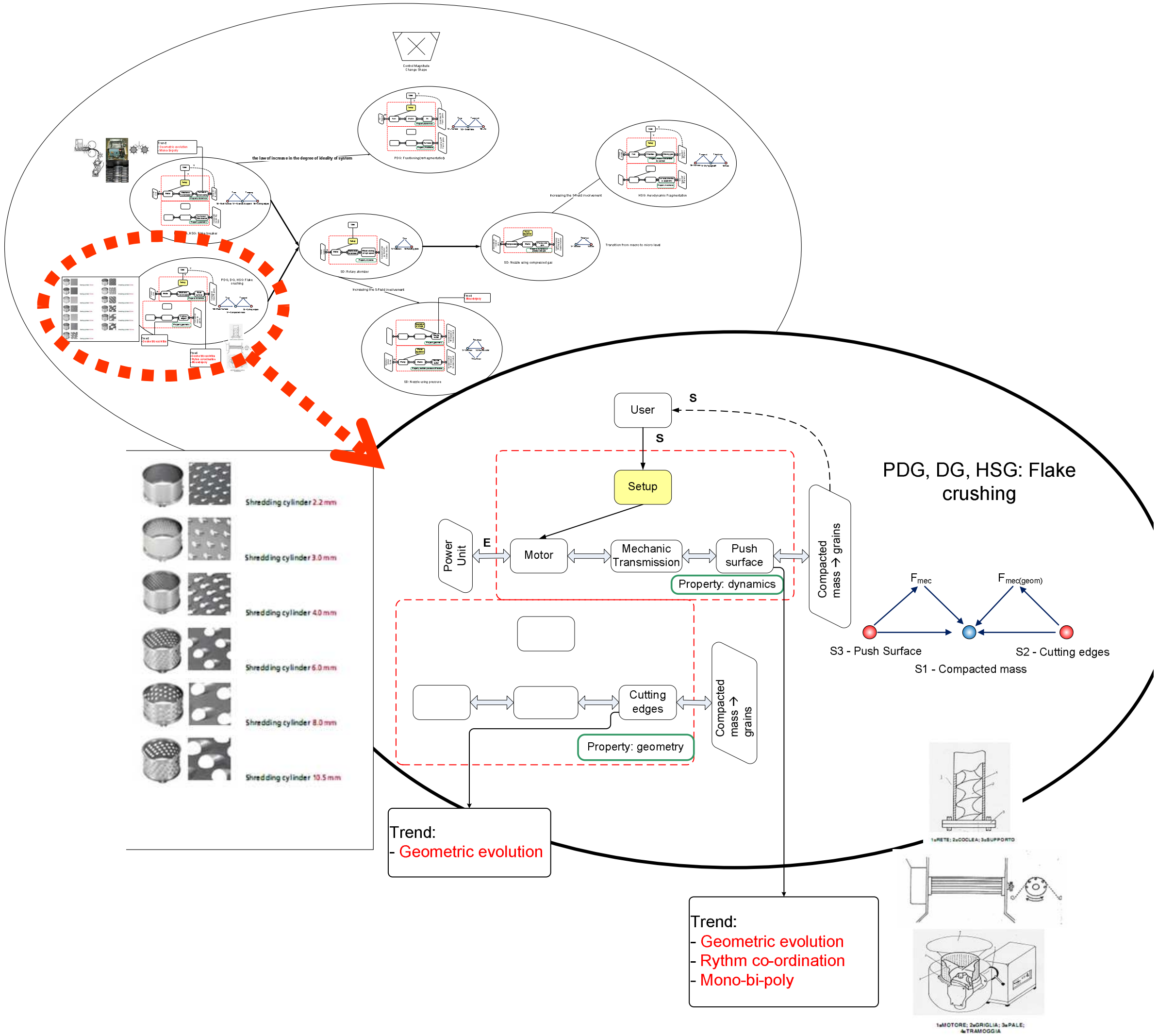
4. Identify the **Evaluation Parameters** defining the performance of each elementary function of the TS modelled at step 1.
5. Identify further **Evaluation Parameters** related to the harmful functions and the resources consumption of each Behavioural Models built at step 2.



Building a Network of Trends (NET)

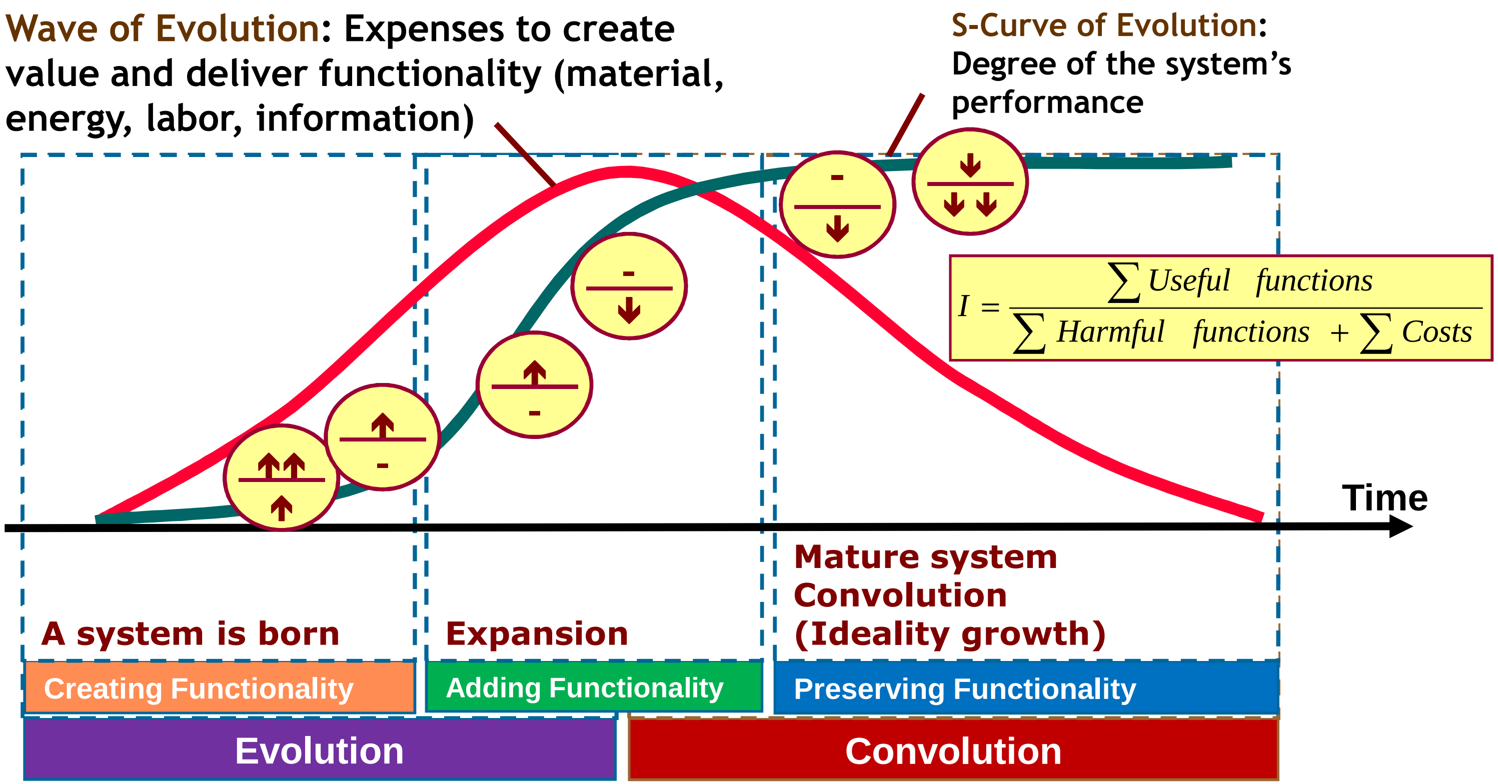
6. Build the Network of Evolutionary Trends

- Order the Minimal Technical System models of each BM of the MUF according to the Law of Transition to Microlevel (change of Behavioral Model-BM)
- Within the same stage of Transition to Microlevel, order the BMs according to the Law of System Completeness (without recurring to the support of external systems or to humans)
- Analyze the interactions between each pair of elements of the Minimal Technical System for each BM of the MUF and perform a comparison according to the TRIZ Laws and Trends of evolution
- Represent as branches of a network the trends identified at previous step



Correlation between Contradictions and Evolutionary Stages

- The growth of the degree of ideality can be compared with the consumption of resources according to the wave model by Salamatov [14].



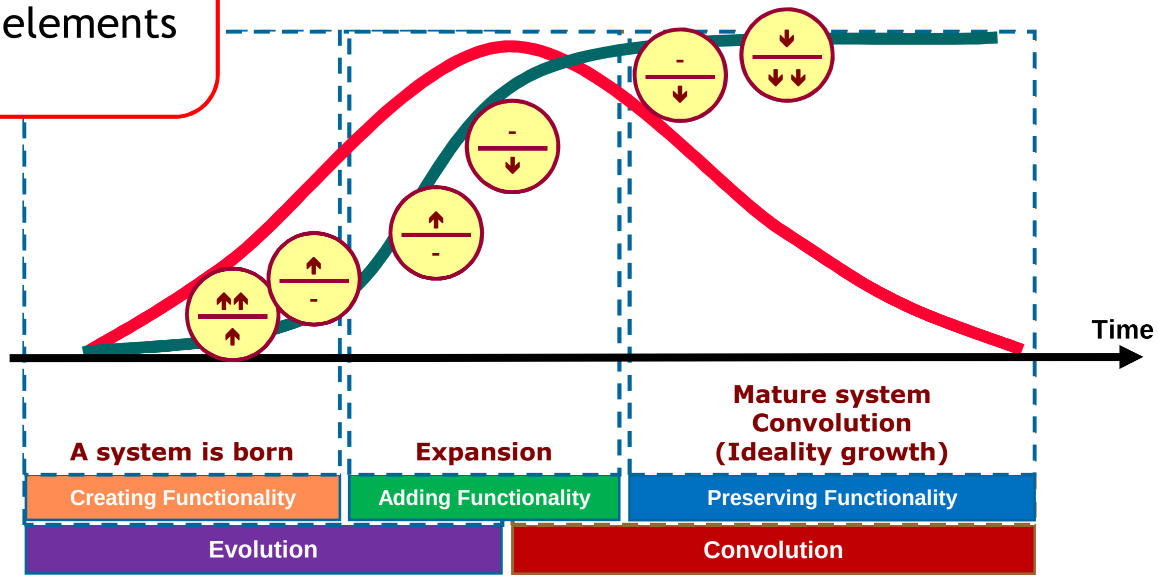
[12] Salamatov, Y.P. "System of The Laws of Technical Systems Evolution". Chance to adventure. Karelia Publishing House, Petrozavodsk, 1991, pp. 7-174 (in Russian).

Correlation between Contradictions and Evolutionary Stages

- Evaluation Parameters related to Ideality:

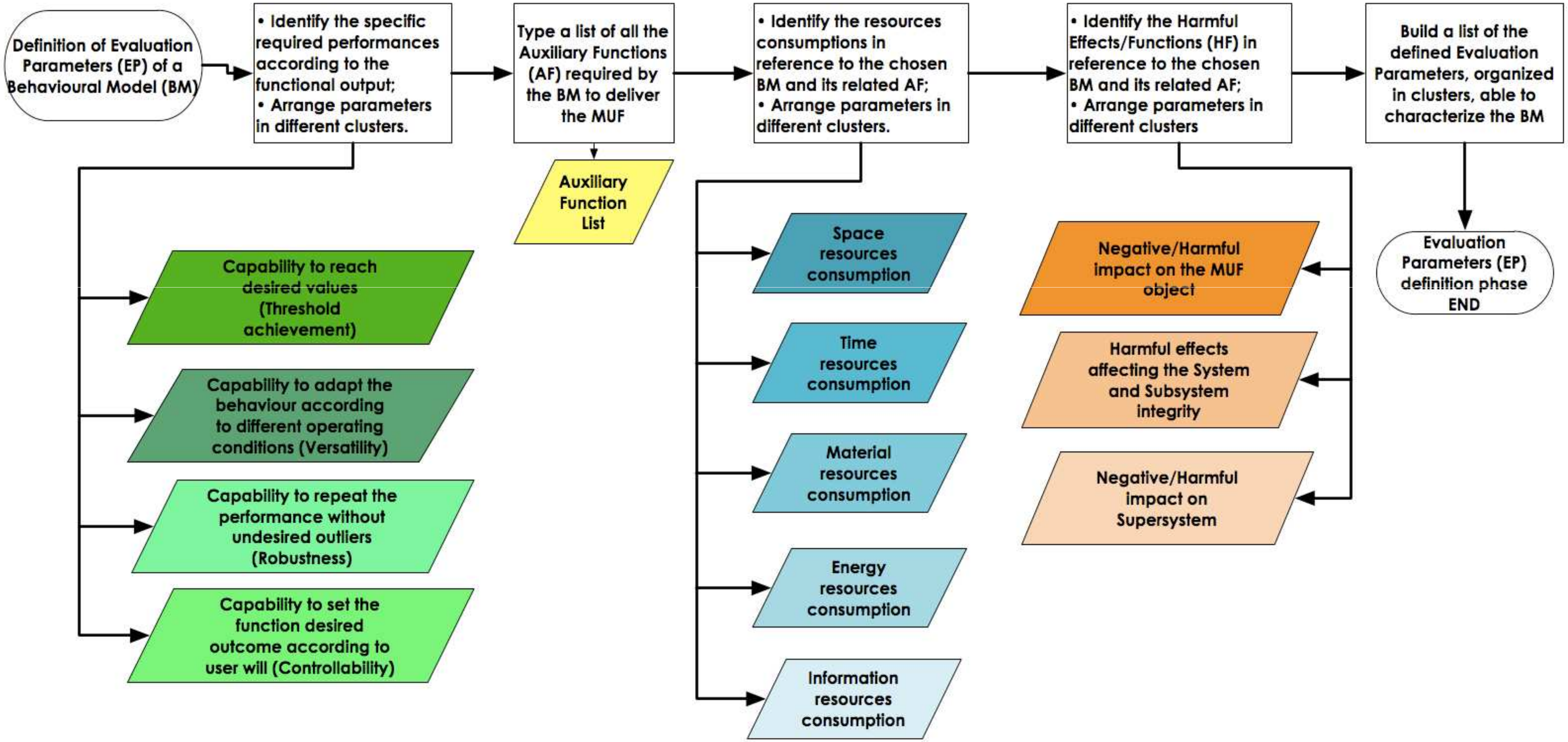
$$I = \frac{\sum UF}{\sum C + \sum HF}$$

- Main Useful Function (MUF) Performance
  - Threshold achievements
  - Versatility
  - Robustness
  - Controllability
- Harmful Functions/Effects:
  - Acting on the MUF object:
  - Acting on system and subsystem elements
  - Acting on the environment
- Resources Consumption:
  - Space
  - Time
  - Information
  - Material
  - Energy



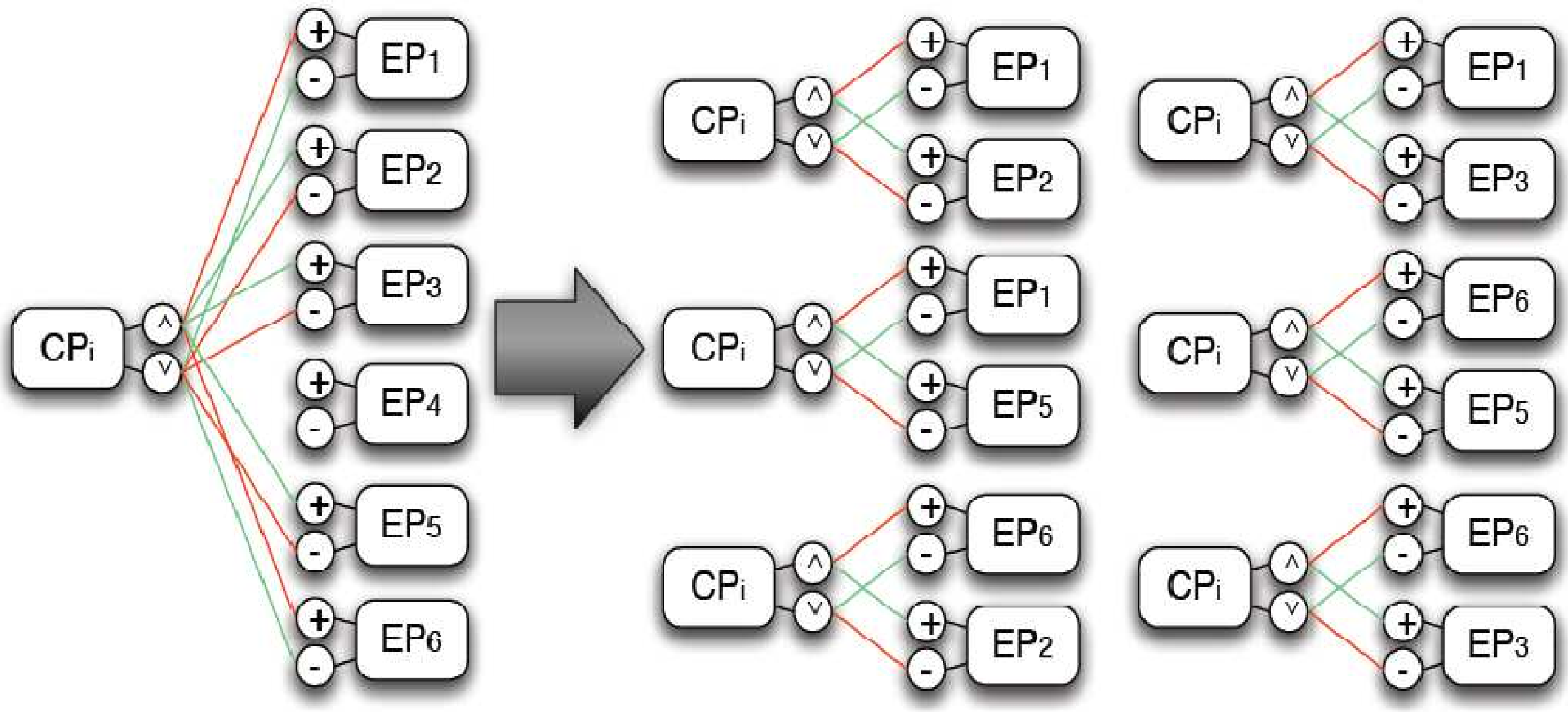
Correlation between Contradictions and Evolutionary Stages

- Algorithm for EP classification:



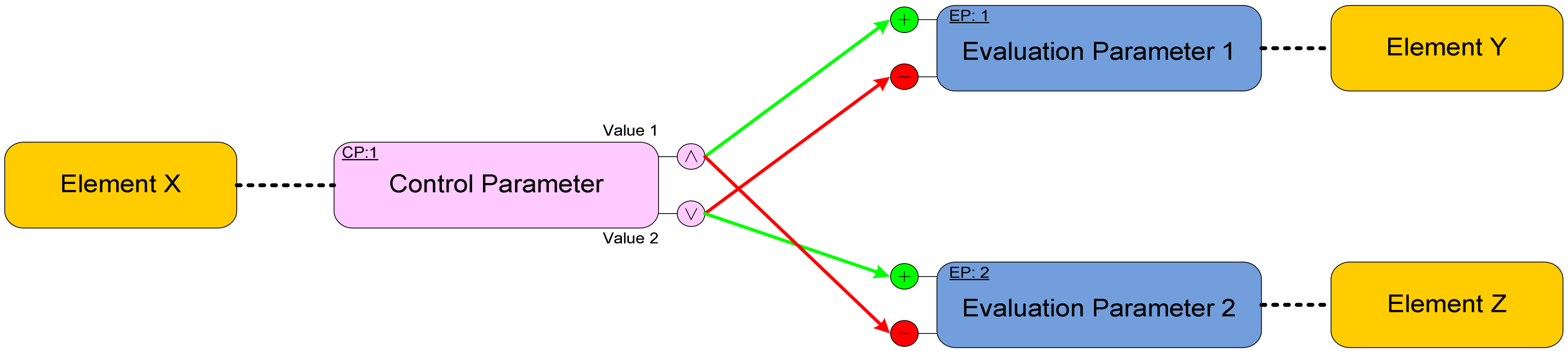
Correlation between Contradictions and Evolutionary Stages

- From Network of Contradictions to a set of elementary contradictions



Correlation between Contradictions and Evolutionary Stages

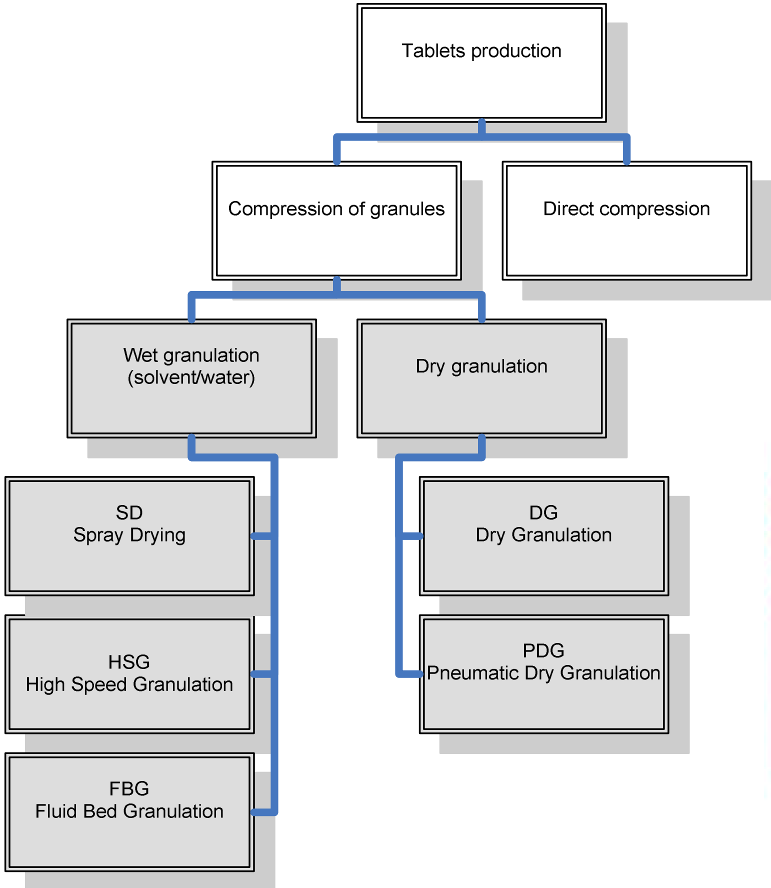
- Classification of elementary Contradictions according to the nature of the pair of Evaluation Parameters
  - Performance (P) vs. Performance (P)
  - Performance (P) vs. Harmful Functions (HF)
  - Performance (P) vs. Resources Consumptions (RC)
  - Harmful Functions (HF) vs. Harmful Functions (HF)
  - Resources Consumptions (RC) vs. Harmful Functions (HF)
  - Resources Consumptions (RC) vs. Resources Consumptions (RC)

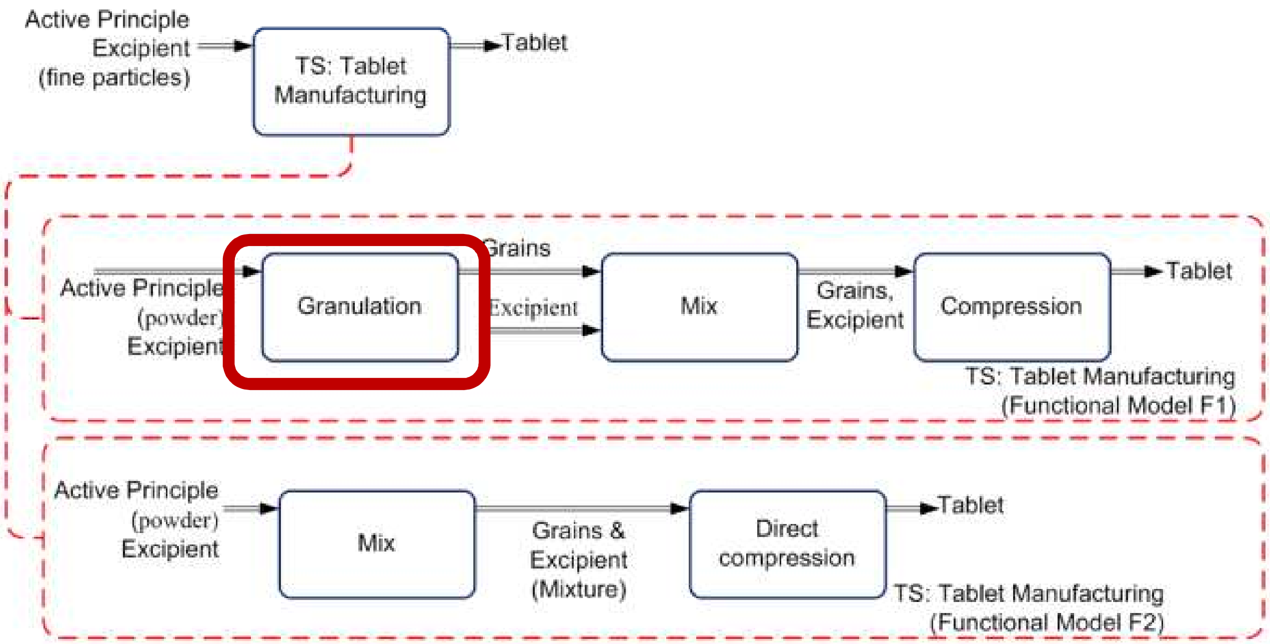


GOAL: Search for correlations between the development of a Technical Systems and the evolution of the Contradictions characterizing its Behavioral Models

Exemplary application: tablets production

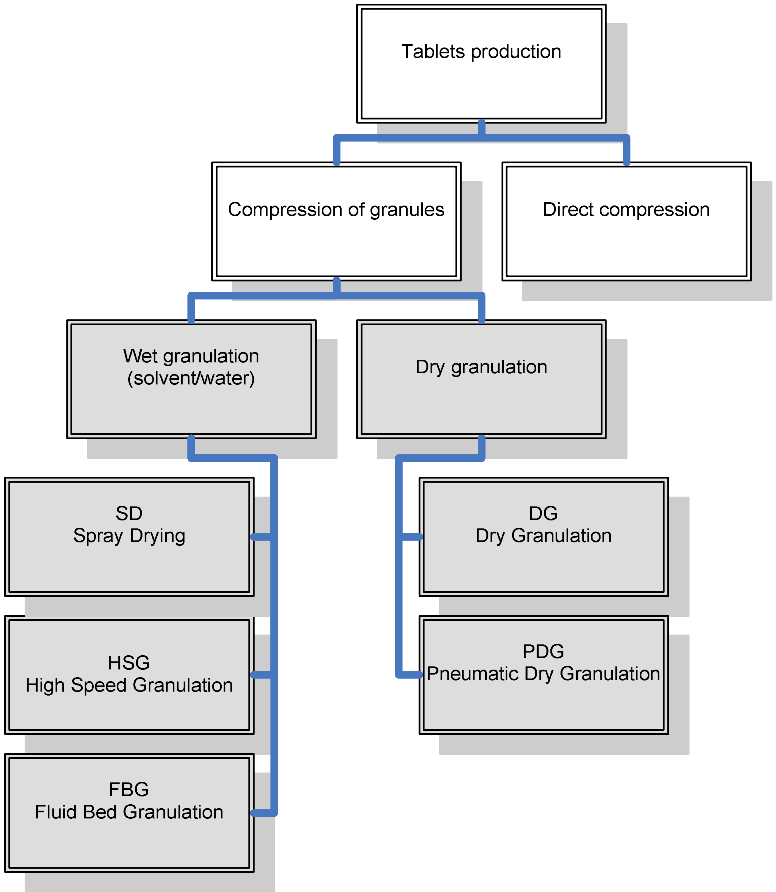
- Production of tablets in the pharmaceutical manufacturing sector: functional analysis





Exemplary application: tablets production

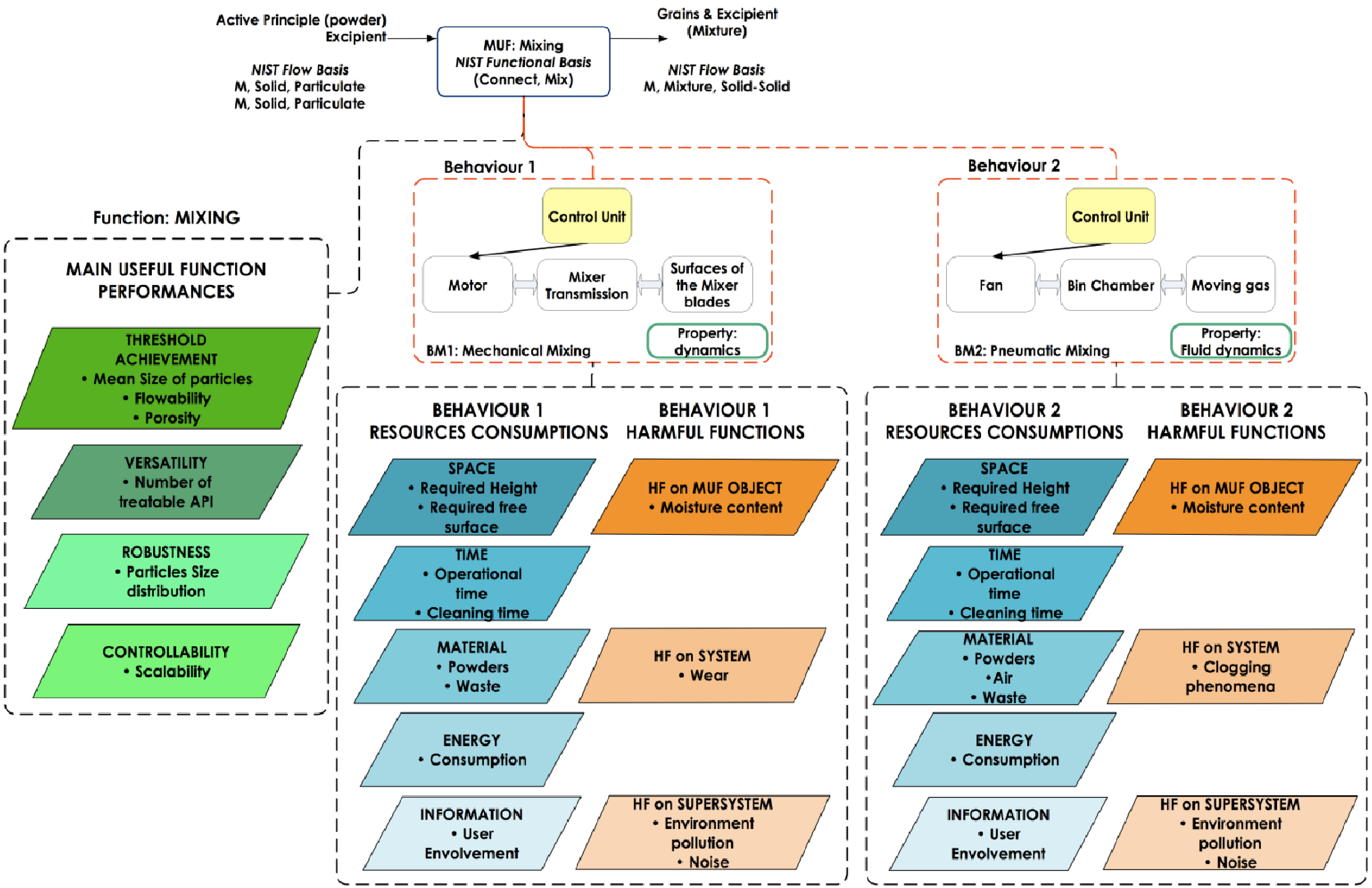
- Behavioral Models associated to the elementary functions of alternative granulation technologies



- BA1: agglomeration of fluidized powders by means of a liquid binder in a closed bin (Fluid Bed Agglomeration);
- BC1: powders compressed into a ribbon by means of two opposite counter rotating rollers (Roller Compaction);
- BD1: pneumatic conveying of particles/powders;
- BM1: mechanical mixing of powders and binders by means of moving surfaces ;
- BM2: pneumatic mixing of powders by fluidization (fluid bed mixing);
- BM3: mixing of powder by means of moving surfaces;
- BF1: mechanical fragmentation of wet mass by means of calibrated nets;
- BF2: mechanical fragmentation of dry compacts (slugs or flakes) by means of oscillating rollers: oscillating granulation;
- BF3: flakes spheronization;
- BS1: Vibro-sieving;
- BS2: PDG “smart” fractioning;
- BS3: cyclone separation;
- BE1: fluid bed drying;
- BE2: dehydration by means of a flow of warm air (oven drying).

Exemplary application: tablets production

- A Minimal Technical System model is built for each Behavioral Model
- Identification and classification of the Evaluation Parameters



Exemplary application: tablets production

- Contradiction analysis: EPs, CPs, and contradictions identified for each BM

BM	EPs	CPs	Contrad. count	Maturity Level
BA1	19	43	**1127**	**G**
BC1	22	16	**633**	**E**
BD1	20	16	**553**	**E**
BE1	19	23	**445**	**G**
BE2	19	22	**456**	**D**
BF1	19	18	**319**	**D**
BF2	21	18	**537**	**G**
BF3	18	14	**274**	**E**
BM1	18	29	**464**	**D**
BM2	19	29	**518**	**G**
BM3	20	19	**521**	**G**
BS1	21	11	**239**	**D**
BS2	21	26	**869**	**E**
BS3	21	21	**566**	**E**

Estimated by Subject Meta-Experts and verified through a qualitative comparison with the order suggested by the TRIZ Laws of Evolution

- **E = emerging**
- **G = growing**
- **D = declining**

Exemplary application: tablets production

- Contradiction analysis: Distribution of contradictions among the BMs

	P vs P	P vs R	P vs HF	HF vs HF	HF vs R	R vs R
BA1	5,5%	39,8%	16,8%	3,9%	18,7%	15,4%
BC1	13,6%	37,3%	24,2%	2,1%	12,0%	10,9%
BD1	8,0%	44,5%	24,6%	4,5%	11,6%	6,9%
BE1	2,5%	45,8%	15,7%	3,4%	18,0%	14,6%
BE2	2,4%	27,9%	14,9%	7,7%	27,2%	20,0%
BF1	5,6%	42,6%	13,8%	0,9%	10,7%	26,3%
BF2	3,7%	34,6%	26,8%	5,6%	18,2%	11,0%
BF3	15,0%	44,2%	22,3%	0,4%	8,0%	10,2%
BM1	2,2%	42,7%	14,9%	0,4%	11,4%	28,4%
BM2	3,5%	38,8%	13,9%	4,2%	21,2%	18,3%
BM3	1,5%	43,4%	26,3%	1,3%	11,7%	15,7%
BS1	0,0%	26,8%	30,1%	5,0%	22,6%	15,5%
BS2	7,6%	30,5%	25,4%	7,2%	18,4%	10,8%
BS3	5,8%	41,0%	21,4%	6,2%	16,3%	9,4%
MAX	15,0%	45,8%	30,1%	7,7%	27,2%	28,4%
AVG	5,5%	38,6%	20,8%	3,8%	16,1%	15,2%
MIN	0,0%	26,8%	13,8%	0,4%	8,0%	6,9%
StdDev	4,4%	6,3%	5,6%	2,5%	5,4%	6,3%
StdDev/Avg	**79,7%**	16,4%	27,1%	**65,1%**	33,7%	**41,3%**

Technology profile	Performance vs. Performance	Harmful functions vs. Harmful functions	Resources vs. Resources
Emerging	41,6%	17,9%	40,5%
Growing	14,8%	16,7%	68,5%
Declining	8,4%	17,6%	74,0%

Average percentage of contradictions for BMs associated to the same stage of evolution

Conclusions and future works

- The authors have already experienced the NET modelling approach in 4 extended case studies related to disabled walkers, wood pellets production, aseptic filling of beverage containers and tablets production (from September 2007 to March 2009)
- Results: definition of a structured set of scenarios to support company's management in the selection of the **most appropriate directions for investment**
- The whole algorithm can be extended (business process reengineering) and improved, but its first part (**system analysis**) has proved to be **effective and repeatable**.
- The proposed **Technology Maturity Assessment** criterion based on the nature of the contradictions characterizing the current stage of development of a technical system have shown promising results and furthers experimental applications are in progress.