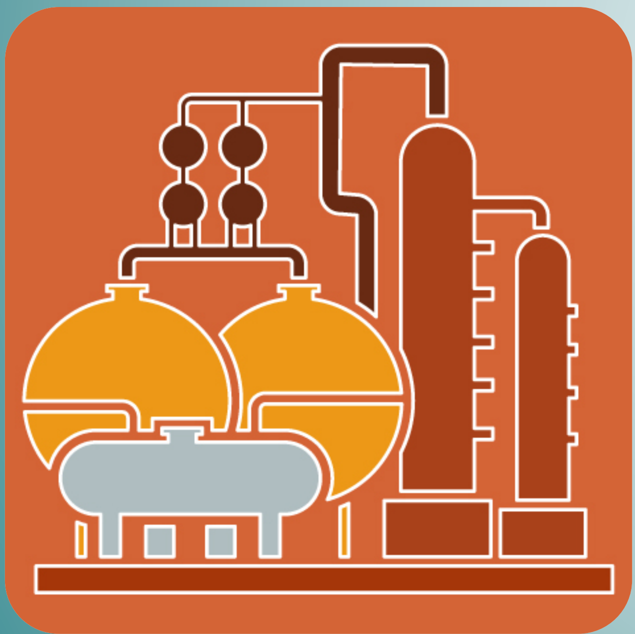
Chemical Process Design / Diseño de Procesos Químicos

Topic 3.3. Introduction to sustainable design



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PRACTICAL CHAPTER

RELEVANT TO LEARNING

1.- Perspective of Sustainable Development: Main environmental and sustainability problems

1.1.- Environmental problems:

Spatial Scales	Residential Local	Landscape National	Sea/fluvial Continental	Ocean/continent Intercontinental	Planet World
Characteristic Processes	Construction of homes Demolition of buildings	Formation of soil processes	Movement of water	Movement of air	Energy balance (IR, UV)
Characteristic Problems	- Noise, odors - Urban air pollution	- Over fertilization. - Soil dehydration. - Deposition of waste.	- Fate of nutrients. - Eutrophication. - Pesticide residues.	- Acidification - Tropospheric ozone. - Radioactive aerosols from nuclear accidents.	- Greenhouse effects. - Depletion of atmospheric O_3 layer.

- **Other problems:**
  - Depletion of scarce resources (ecological and economic importance).
  - Widening gap between rich/poor (social and economic issues).
  - Technological development without precaution (technological issue).
  - Clean water and food scarcity (social and economic importance).
  - Biodiversity reduction (ecological problem).

1.- Perspective of Sustainable Development: Main environmental and sustainability problems

1.2.- Environmental problems: waste in chemical production:

Sector	Production kg/y	$kg_{waste+subp} / kg_{product}$
Oil refinery	$10^6 - 10^8$	0.1
Commodities	$10^4 - 10^6$	(< 1) - 5
Fine Chemicals	$10^2 - 10^4$	5 - 50
Pharmaceuticals	$10^1 - 10^3$	25 - (> 100)

- **Alternative products, raw material, processes, chemical routes.**

- **Reuse of waste.**

1.- Perspective of Sustainable Development: Main environmental and sustainability problems

1.2.- Environmental problems: waste in chemical production:

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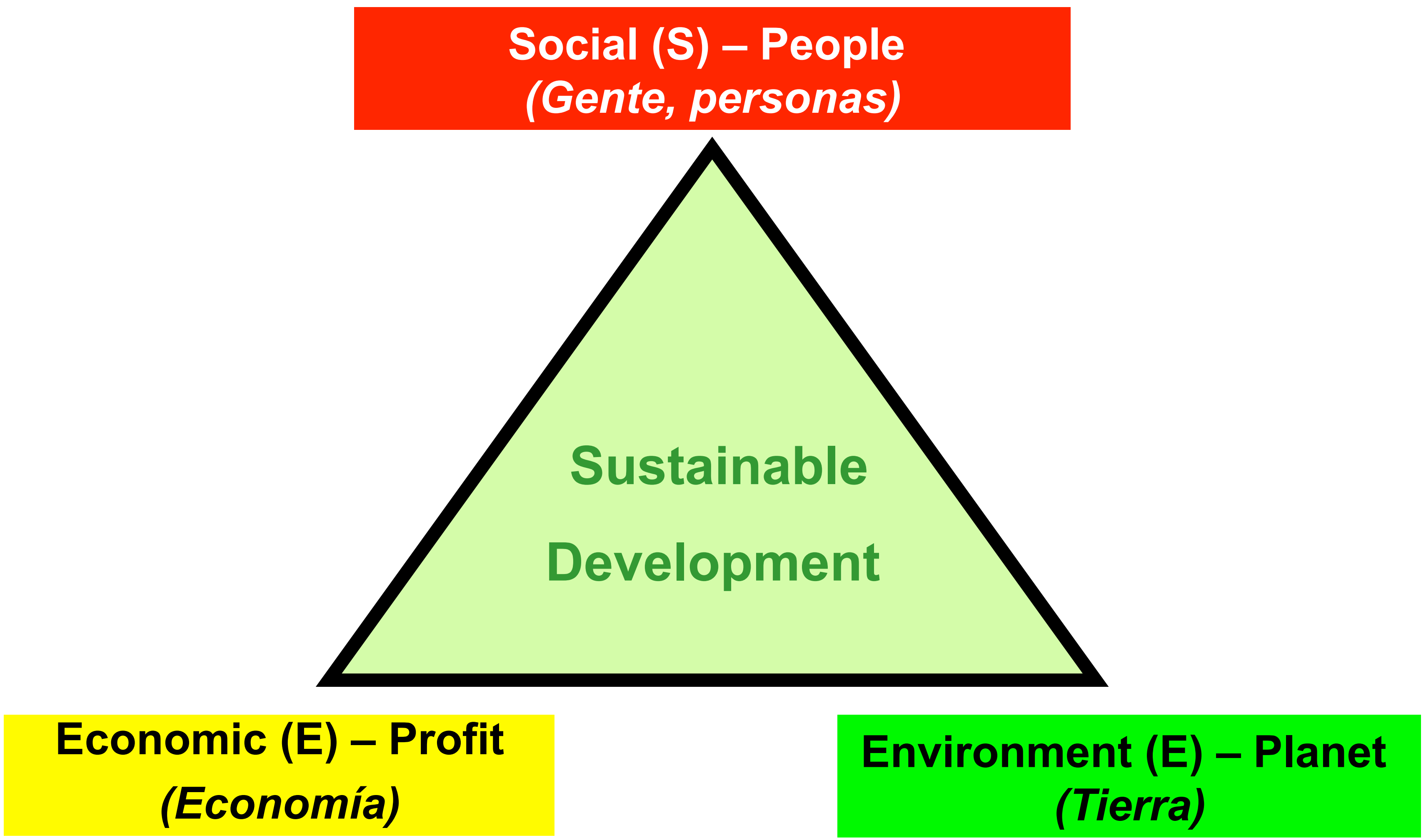
High amounts of waste in all cases

- **Alternative products, raw material, processes, chemical routes.**
- **Reuse of waste.**

1.- Perspective of Sustainable Development:

Sustainable Development – Triple P



1.- Perspective of Sustainable Development: Non-sustainable technological solutions

- **High chimneys for acidic flue gases:**

  1960 Smog in cities → Chimneys > 200 m. Transboundary acidification.

- **CFCs use:**

  1960-70' inert gases → 1974 stratospheric ozone broke → UV Radiation.

- **HFC replacement of CFC for refrigeration:**

  The Global Warming Potential (GWP) of this gas is 1000 times higher than CO_2.

- **MTBE in petrol as replacement of lead components:**

  Contamination of drinking waters.

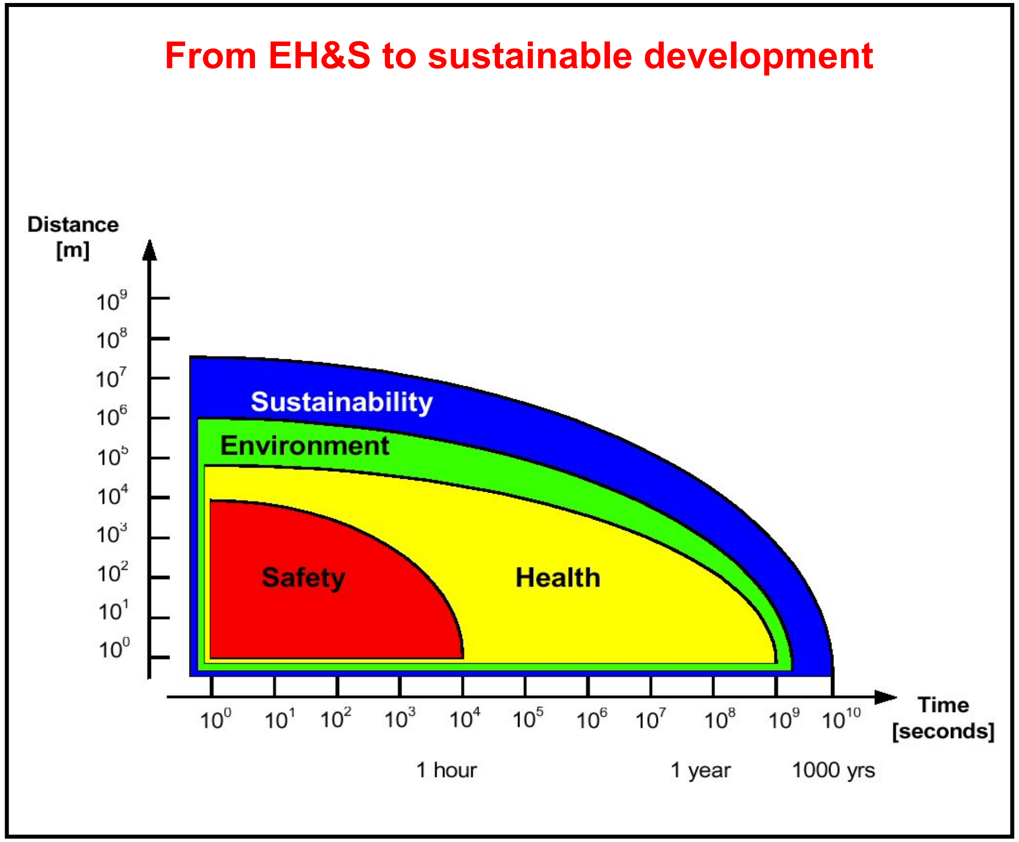
- **Brent Spar (Shell) oil platform:**

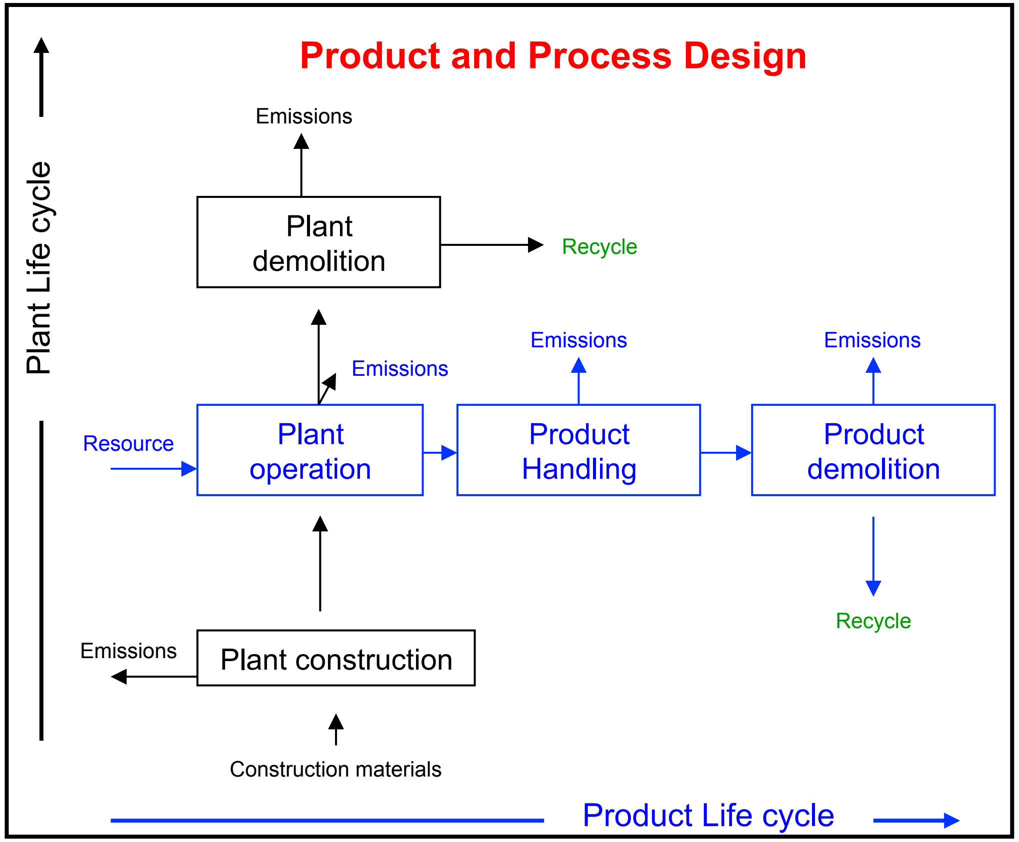
  Activity ceased → Deep sea disposal → Greenpeace involvement → re-use much of the main structure in the construction of new harbor facilities in Norway.

The problem to be solved was defined too narrowly in space, time and life cycle phases. Longer-term effects were not taken into account. Precaution principle was not known and/or applied.

2.- Sustainable Development and Chemical Industry:

- **Chemical Industry:**
  - Great importance in modern society.
  - Originates important environmental problems.
  - Knowledge to solve environmental problems.
- **Chemical Engineering** can play an important role in solving sustainability problems.





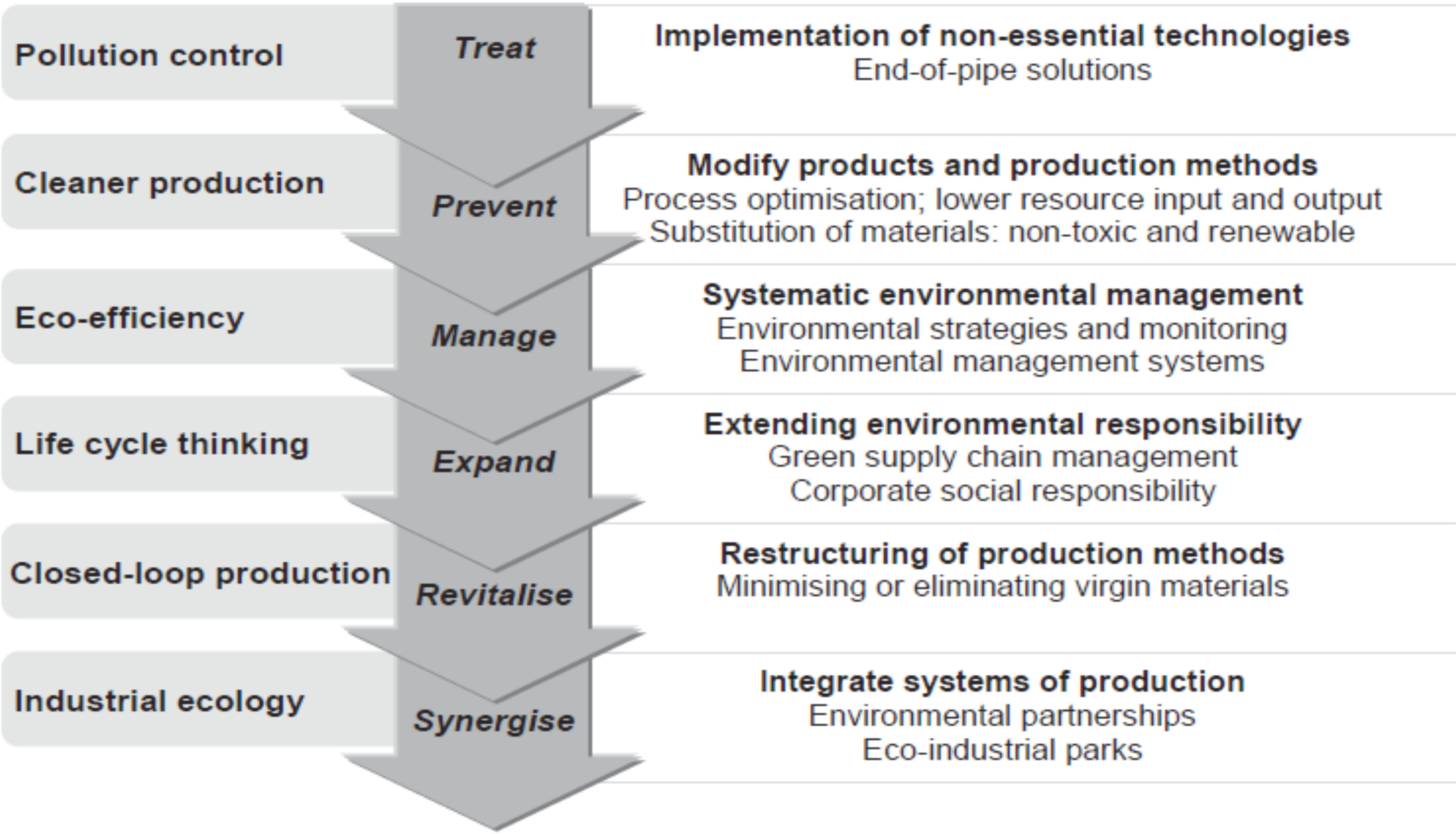
3.- Sustainable Production, Eco-efficiency and Eco-innovation

- **Sustainable Production:** the creation of goods and services using processes and systems that are: non-polluting, conserving of energy and natural resources, economically viable, safe and healthful for workers, communities, and consumers, and socially and creatively rewarding for all working people (Nasr & Thurston, 2006).

- **Eco-efficiency:** a state that can be reached through *"the delivery of competitively priced goods and services that satisfy human needs and bring quality of life while progressively reducing environmental impacts of goods and resource intensity throughout the entire life cycle to a level at least in line with the Earth's estimated carrying capacity"* (WBCSD, 1996). Producing more goods and services while using fewer resources and creating less waste and pollution (EC, 2005).

- Nasr, N. & Thurston, M. (2006): *«Remanufacturing: a key enabler to sustainable product systems»*. Rochester Institute of Technology. Rochester, NY.
- World Business Council for Sustainable Development (WBCSD) (1996): *«Eco-efficient leadership for improved economic and environmental performance»*. WBCSD, Geneva.
- European Commission (EC) (2005): *«Doing more with less: green paper on energy efficiency»*. Office for Official Publications of the European Communities. Luxembourg.

3.- Sustainable Production, Eco-efficiency and Eco-innovation



The evolution of sustainable manufacturing concepts and practices (OECD, 2009).

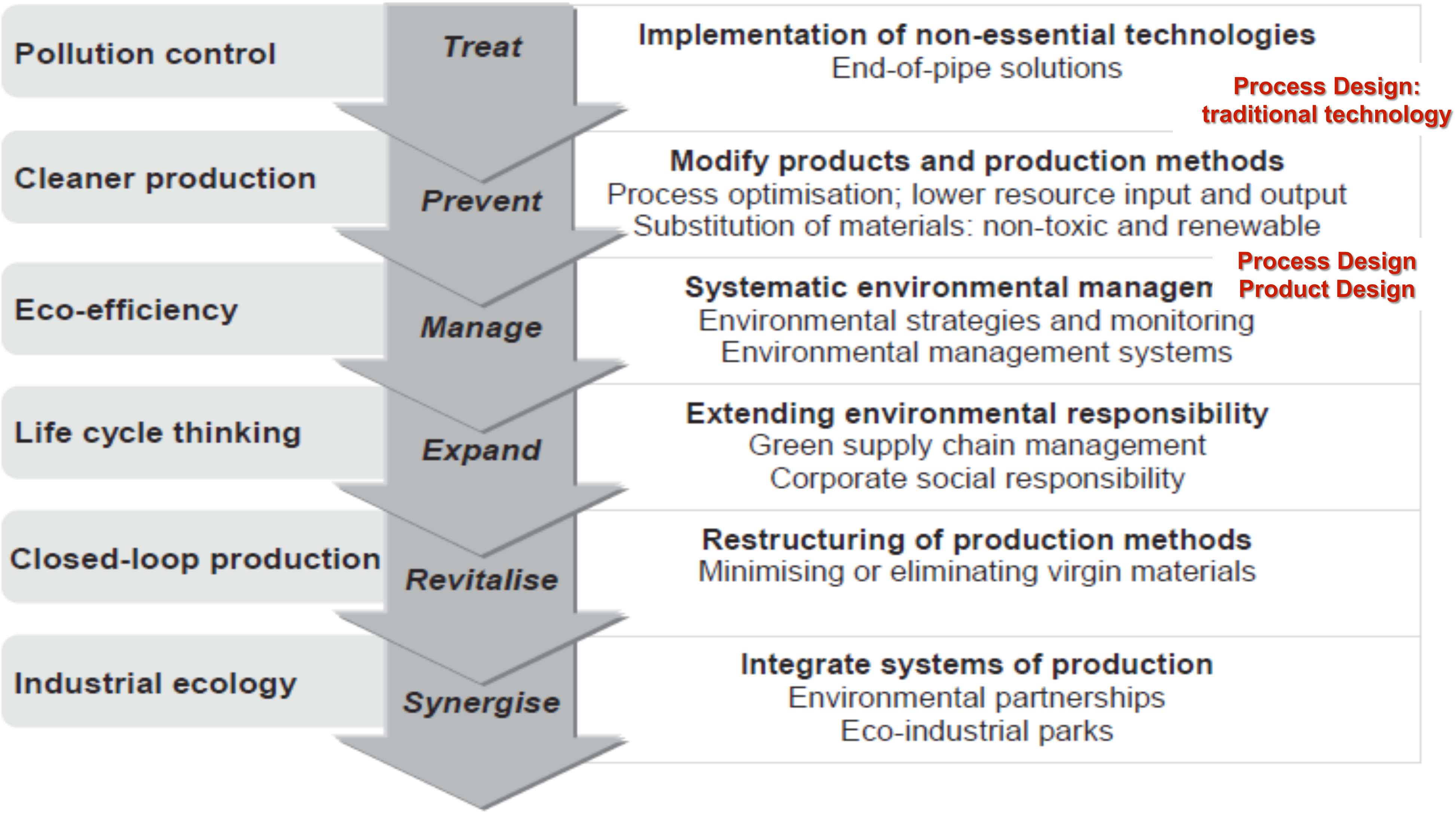
3.- Sustainable Production, Eco-efficiency and Eco-innovation

Pollution control	*Treat*	**Implementation of non-essential technologies** End-of-pipe solutions
Cleaner production	*Prevent*	**Modify products and production methods** Process optimisation; lower resource input and output Substitution of materials: non-toxic and renewable
Eco-efficiency	*Manage*	**Systematic environmental management** Environmental strategies and monitoring Environmental management systems
Life cycle thinking	*Expand*	**Extending environmental responsibility** Green supply chain management Corporate social responsibility
Closed-loop production	*Revitalise*	**Restructuring of production methods** Minimising or eliminating virgin materials
Industrial ecology	*Synergise*	**Integrate systems of production** Environmental partnerships Eco-industrial parks

Process Design: traditional technology

The evolution of sustainable manufacturing concepts and practices (OECD, 2009).

3.- Sustainable Production, Eco-efficiency and Eco-innovation



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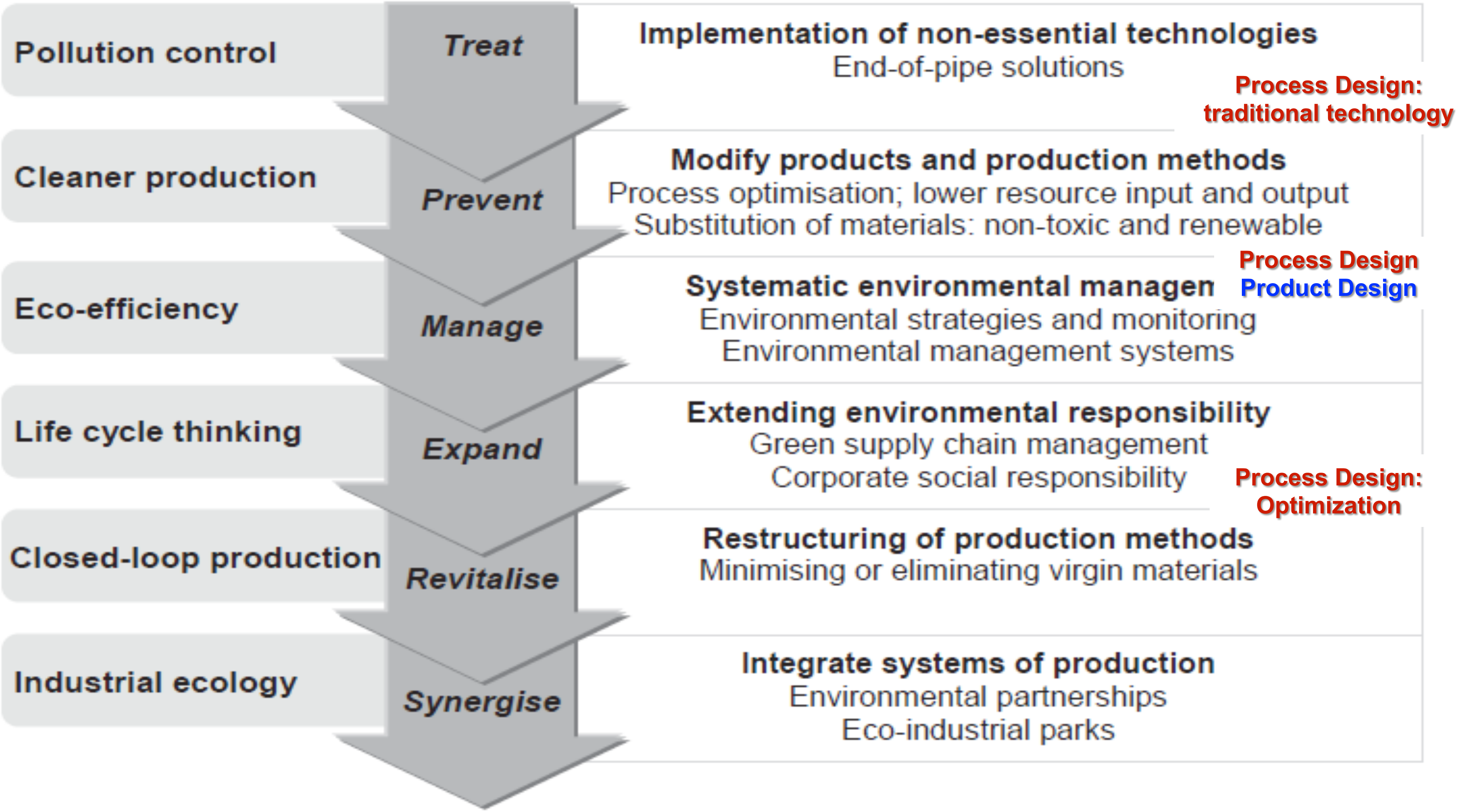
3.- Sustainable Production, Eco-efficiency and Eco-innovation



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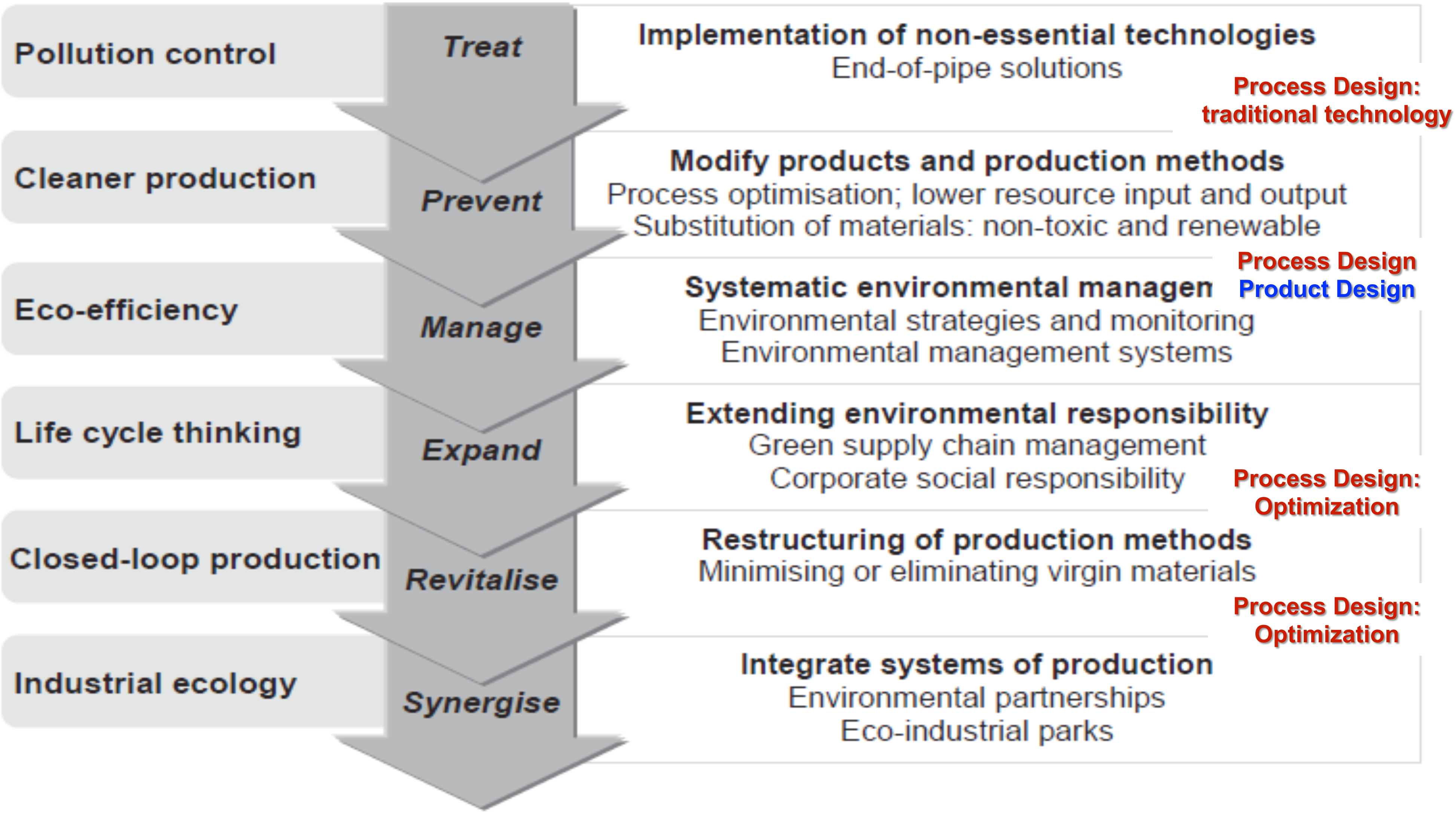

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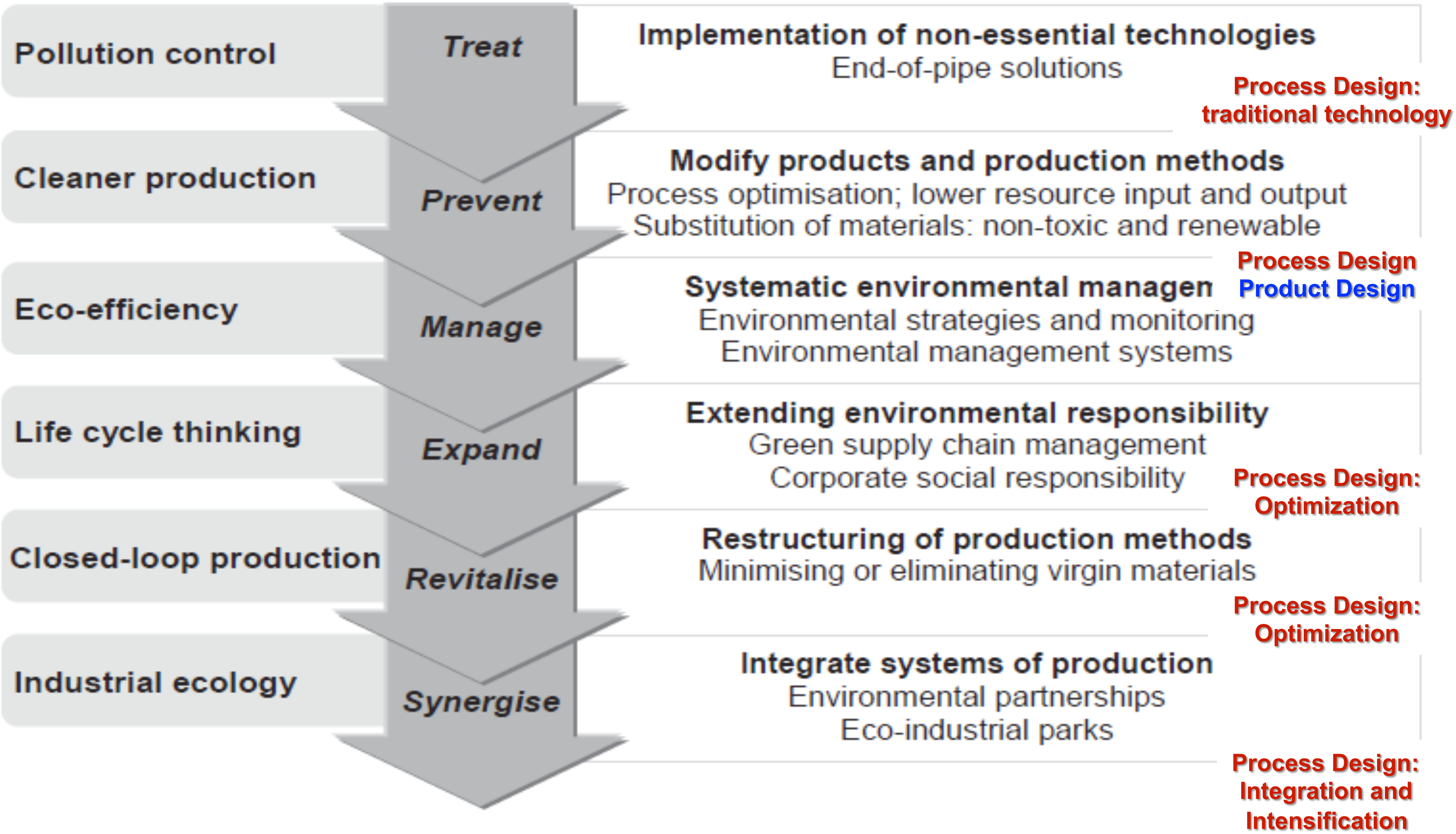
3.- Sustainable Production, Eco-efficiency and Eco-innovation



The evolution of sustainable manufacturing concepts and practices (OECD, 2009).

3.- Sustainable Production, Eco-efficiency and Eco-innovation

- **Innovation:** the implementation of new, or significantly improved, products (goods or services), or processes, marketing methods, or organizational methods in business practices, workplace organization or external relations (OECD and Eurostat, 2005*).*

- **Eco-innovation:** the implementation of new, or significantly improved, products (goods and services), processes, marketing methods, organizational structures and institutional arrangements which, with or without intent, lead to environmental improvements compared to relevant alternatives.

- **Eco-innovation vs. innovation:**
  - It is not an open-ended concep t as it represents innovation which explicitly emphasizes the reduction of environmental impacts, whether intended or not.
  - Eco-inn ovation is limited to innovation in products, processes, marketing methods and organizational methods, but also includes innovation in social and institutional structures (Rennings, 2000).

- OECD and Statistical Office of the European Communities (Eurostat) (2005): *«Oslo manual: guidelines for collecting and interpreting innovation data»*. 3rd Ed. OECD. Paris.
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3.- Sustainable Production, Eco-efficiency and Eco-innovation

Design to eco-innovation

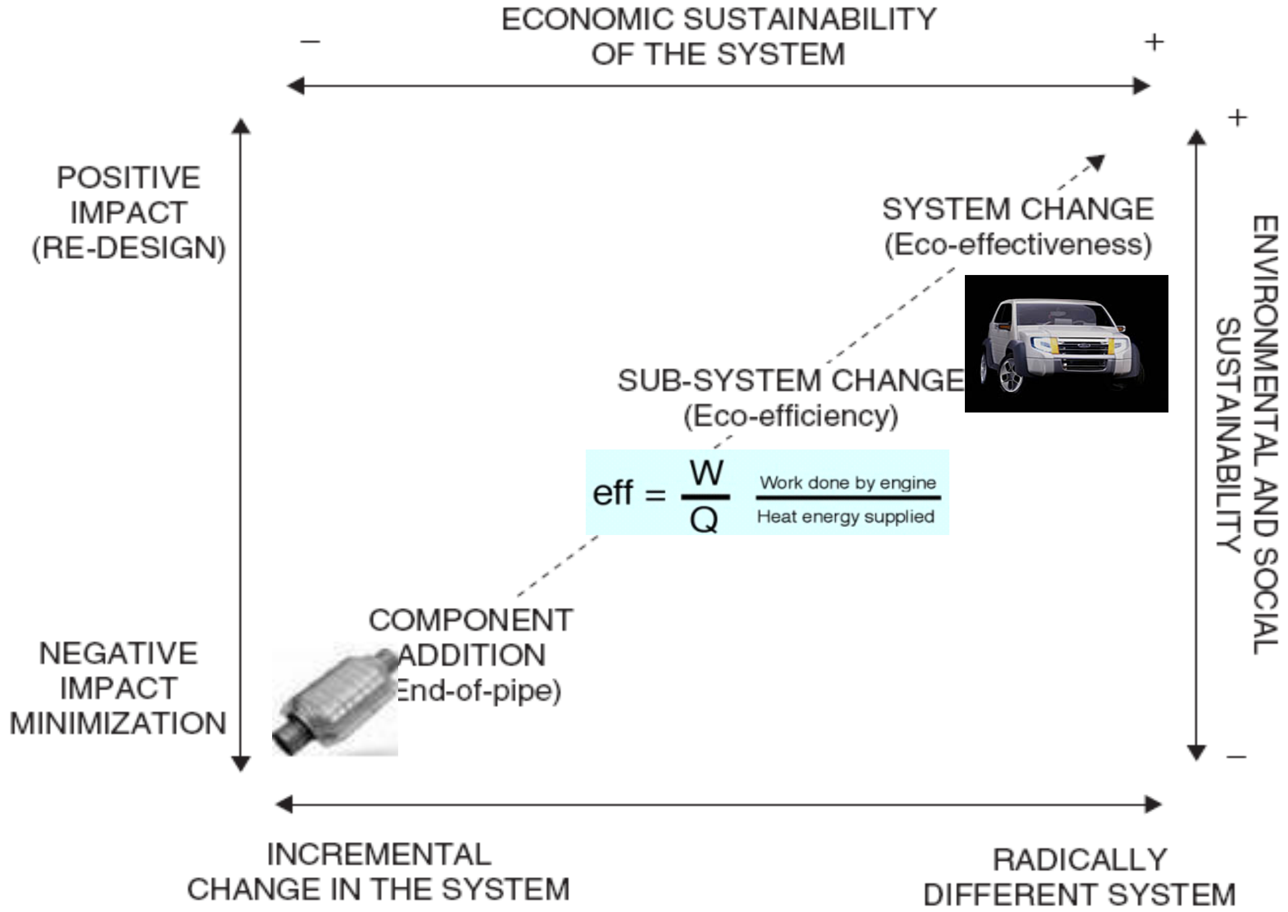


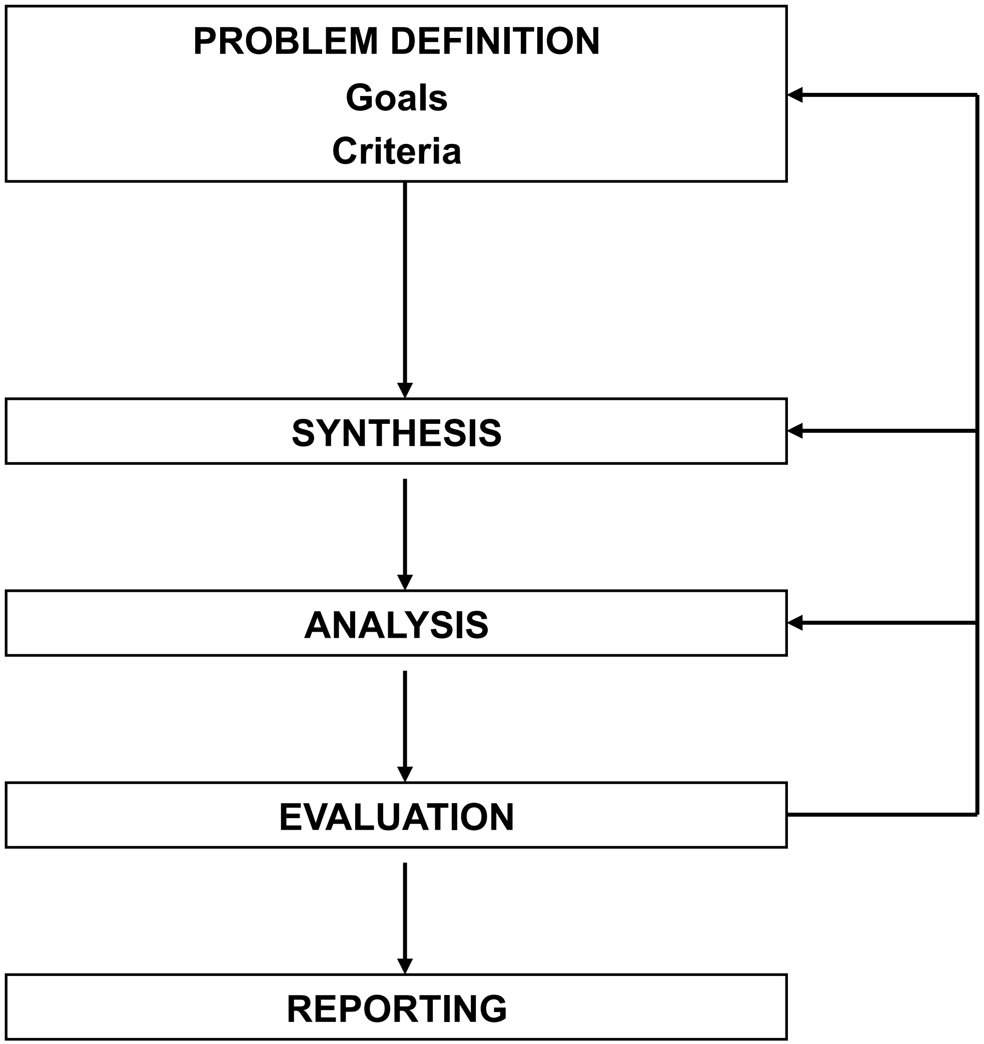
Figure 2.1 Design framework for eco-innovation in view of radical and incremental change and negative and positive impacts on the environment. The highest sustainability and competitiveness benefits are likely to occur in the top right-hand corner of the figure

Source: Authors' own figure.

Adapted from Carrillo *(et al.)*, (2009).

4.- Designing Sustainable Products and Processes

General Design Procedure



4.- Designing Sustainable Products and Processes

4.1.- Problem Definition

PROBLEM DEFINITION

Goals

Criteria

GOALS

Integration of economic, societal and ecological constraints *at the initial step of the conceptual process design.*

Stakeholders participation.

Include Management (business strategy, supply chain, marketing) and R&D (knowledge and innovation).

4.- Designing Sustainable Products and Processes

4.1.- Problem Definition

CRITERIA

To be applied to a specific scenario with a defined boundary.

- **Economic Criteria:**
  - **Capital Investment, Operational Costs, Externalities.**
  - **Benefits, NPV, IRR.**
- **Environmental Criteria:**
  - **Renewability: contribution of renewable energy and feedstock.**
  - **Waste reduction: waste stream reduction per unit operation.**
  - **Decommissioning: determining the long-term effect of the plant.**
  - **Pressure over sinks (air, water, soil).**
- **Societal Criteria:**
  - **Desirability: technology must fit into a current and future societal context.**
    (Conveniencia) **(Pollution prevention, responsible care, salary, safety, work schedule).**
  - **Availability: technology BAT and easily accessible.**
    http://eippcb.jrc.ec.europa.eu/reference/
  - **Flexibility: highly flexible as regards its impact on society and the level of acceptance.**

4.- Designing Sustainable Products and Processes

4.2.- Synthesis of Alternatives

SYNTHESIS

LCA approach (Chemical Route Selection), Task identification and Closed Cycle.

- **Chemical Route Selection based on LCA:**
  - **Based on taking a holistic view of a product or service, from raw material through production to distribution and final disposal of all waste. Used for chemical route selection in the basic chemistry stage of the design.**
  - **Based on the most sustainable Supply Chain (or whole process that is required to produce the desired chemical).**
- **Task Identification:**
  - **Process Flowsheet Synthesis through the identification of basic operations.**
  - **Hierarchical approach of Douglas (Irreducible Structure): Development of conventional designs with less opportunities for innovative integration.**
  - **Superstructure (Reducible Structure): All possible alternatives.**
- **Closed Cycle:**
  - **No flows are allowed to enter the process except the feed and product flow.**

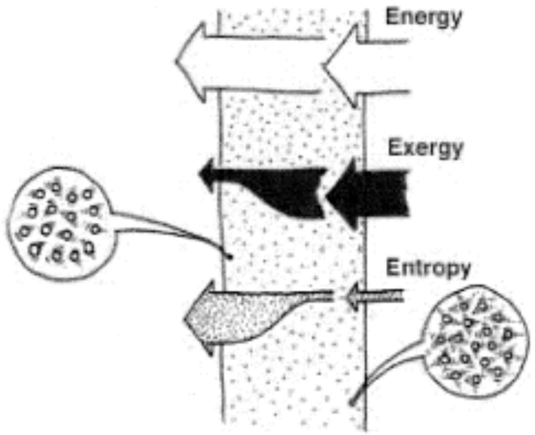
4.- Designing Sustainable Products and Processes

4.3.- Analysis of Alternatives

ANALYSIS

Analysis against the criteria set in the problem definition phase. Two additional remarks: Exergy analysis and forum discussion.

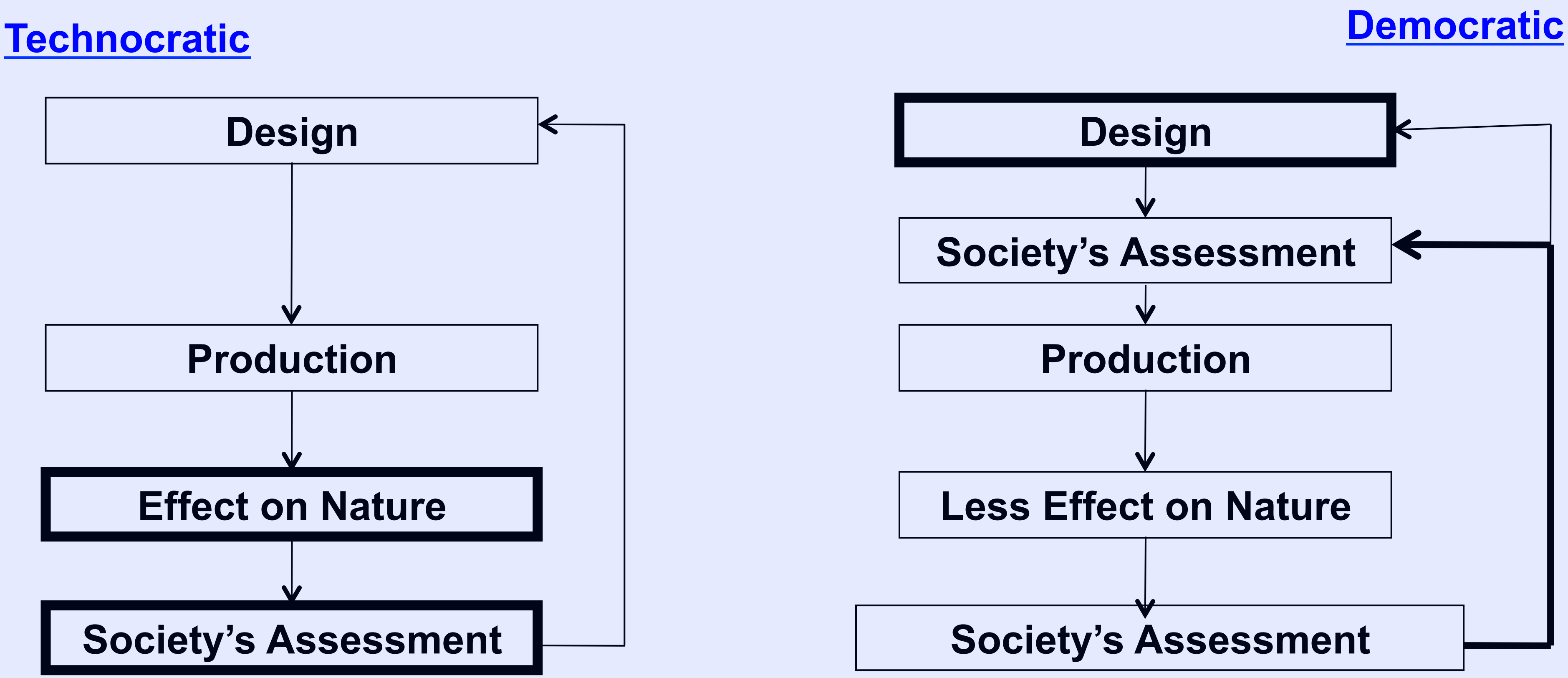
- **Exergy analysis:**
  - Exergy is the maximum amount of work that can be done by a subsystem as it approaches thermodynamic equilibrium with its surroundings by a sequence of reversible proce-sses. Exergy measurements are made relative to an equili-brium state in which there are no gradients of any kind. Thus, the exergy of a subsystem is a measure of its 'distan-ce' from equilibrium and is the energy that is available to be used. Mechanical exergy is known as kinetic energy, while thermal exergy is more familiarly known as heat.
  - Important concepts → in the design of energy-efficient machines and CO_2 emissions.
  - Chemical exergy → used in chemical engineering and thermoeconomics for process optimization, but also in economics and environmental science.



Energy, exergy, and entropy flow in and out a building envelope system. The amounts of energy flowing in and out are the same under thermally steady-state condition according to the law of energy conservation; the amount of entropy flowing out is larger than flowing in according to the law of entropy increase. The amount of exergy flowing out is smaller than flowing in, since exergy is consumed within the system to produce entropy.

Forum Discussion (Stakeholders):

Involving the public in the design



Change in the design process taking society's assessment into account

4.- Designing Sustainable Products and Processes

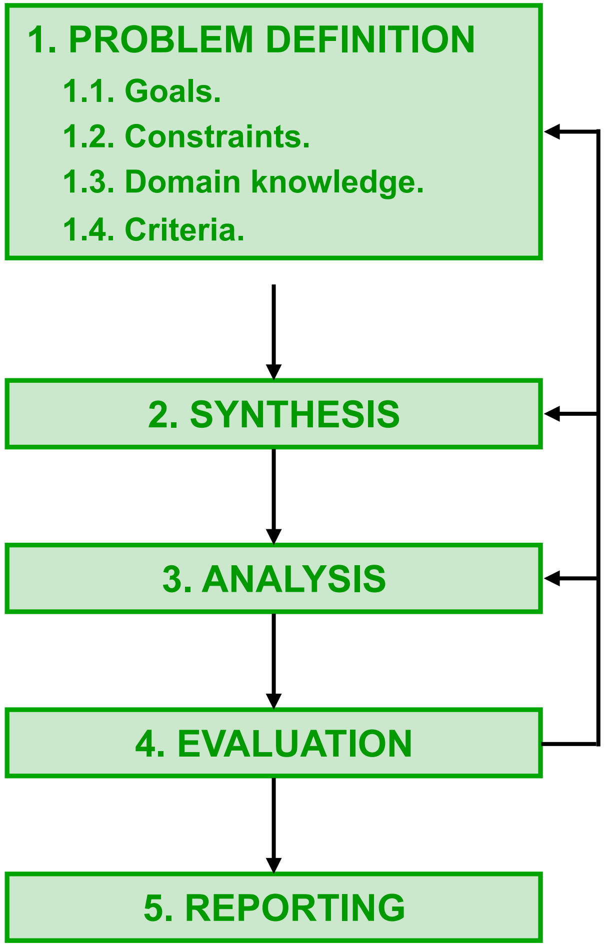
4.4.- Evaluation of Alternatives and Reporting

EVALUATION-REPORTING

Choosing the final design and presentation of the flowsheet.

- Trading off:
  - A design must be the solution which best satisfies all parties within the given constraints → most optimal compromise.
  - The final weight given to the criteria is strongly dependent on the problem definition phase.
- Flowsheeting:
  - Presentation of the final PDF → PDF + Mass and Energy Balances + Economic evaluation + Safety studies + Environmental studies.

Summary of the General Design Procedure



Design Steps	Remarks
Problem Definition: - Goal. - Scope. - Domain knowledge. - Constraints: • Economic. • Ecological. • Societal.	Define the scope and goal of the design. What knowledge is necessary and what knowledge is available? What kind of design, what kind of process and what kind of approach is best for solving the problem?
Synthesis: - Chemical route selection. - Task identification. - Flowsheet generation. - Closed cycle approach.	What methods are required to design and optimize the process?
Analysis: - Exergy Analysis. - Forum Discussion.	What issues must be checked to accept the final design?
Evaluation and Reporting: - Trade-off. - Flowsheeting.	How is the final design presented and how is its value proven to the various stakeholders?

5.- Case studies

- **TOOLS:**
  - Process simulators + Mathematical programming packages + **Environmental databases:** SimaPro, TEAM, GABI.

- **METHODOLOGY:**
  - Calculate the emissions released, include entire **Life Cycle** of the product, analysis from the cradle to the grave through **DAM = environmental damage** (expressed in GWP100 or EI99).
    - **CML 2000 [GWP100]** = global warming potential for a time horizon of 100 years expressed in kilograms of carbon dioxide per kilogram of emission (considering a global scale).
    - **EI99** = Eco-indicator 99 includes 11 impact categories, which are further aggregated into a single metric into 3 damage categories:
      - Human health: DALYs (Disability Adjusted Life Years).
      - Ecosystem quality: PDF · m^2 · yr (Potentially Disappear Fraction of Species).
      - Resources: MJ surplus energy · kg^{-1}.

- **CASE-STUDIES at different levels:**
  - **Supply-chain:** Hydrogen, bioethanol.
  - **Manufacturing Plant:** Hydrodealkylation of toluene, sugar cane, MSWI.
  - **Production Line:** Industrial wastewater networks, absorption cooling systems.
  - **Unit Operations:** Distillation, CO_2 absorption by MEA.

6.- Further Reading and References

- Carrillo-Hermosilla, J.; Del Río, P. & Könnölä, T. (2009): *«Eco-innovation: when sustainability and competitiveness shake hands»*. Palgrave-Macmillan. Hampshire: http://publications.jrc.ec.europa.eu/repository/handle/JRC56837.
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- SusChem (2009): *«The european technology platform for sustainable chemistry»*. IAP Update 2009. Reaction & Process Design: http://www.suschem.org.

Practical Chapter

- **Application of sustainable design tactics to case study.**
- **Application of sustainable tactics to your process design project.**

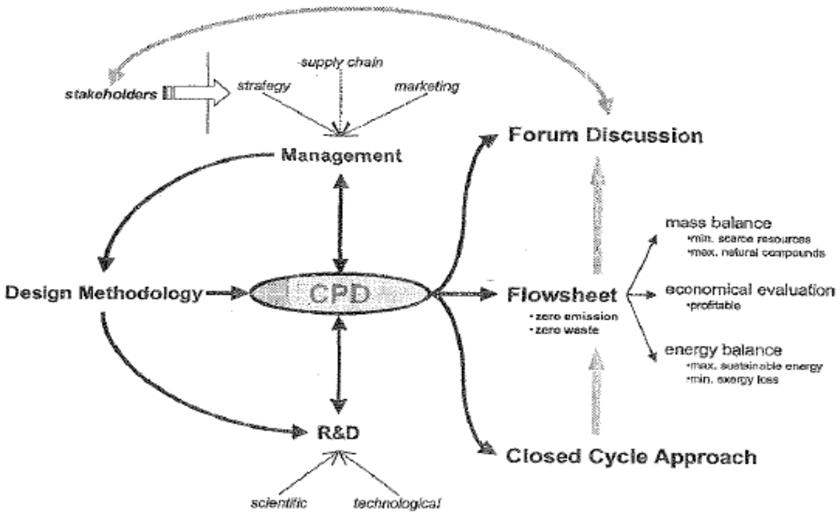
Relevant to Learning

- **Sustainability problems in chemical production.**
- **Sustainable Production, Eco-efficiency, Innovation and Eco-innovation.**
- **Criteria for Designing sustainable products and processes.**

ADDITIONAL INFORMATION

Goal Description

- System boundary definition with complete closed cycles.
- Stakeholder analysis: issues which influence management are dependent on the stakeholders.
- Need identification: vague demand of the public → engineering constraints for the designer.
- Scenario Building: externalities influencing the process are incorporated into the scenario by an external panel. External effects determined and their influence on the design evaluated.

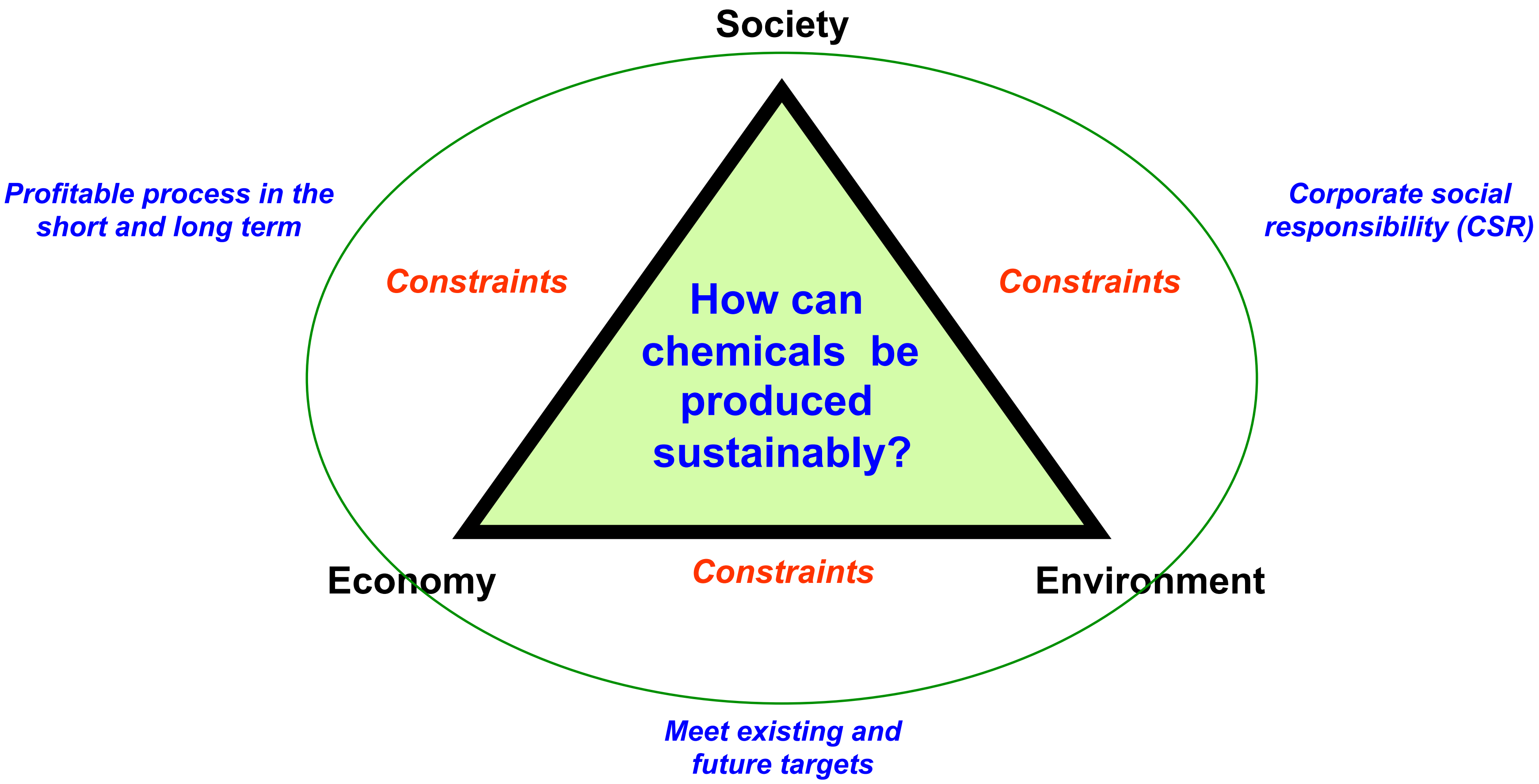


Place of the Conceptual Process Design (CPD) within its context

Management (business strategy, supply chain, marketing) and R&D (knowledge and innovation) are strong facilitators of the conceptual process design.

Constraints Definition

- Constraints are the final boundary conditions that a design has to meet.
- The environment, society, and economy determine the constraints of sustainable production → Optimum design located somewhere within the triangle.



Economic Constraints

- **Principles:** profitable process in the short and long term.
- **Criteria:**
  - Capital Investment (short term).
  - Operational Costs (short term).
  - Externalities (long term).

Ecological Constraints

- **Principles:**
  - Material streams from the plant and used by the plant should not disturb irreversibly existing natural streams (e.g. restricted emissions of acid rain gases).
  - Streams between the plant and the ecosphere must be within the carrying capacity of soil, water and air (e.g. responsibility of feedstock source).
  - Material streams extracted directly from nature into the plant have to be part of a know closed elemental cycle (e.g. monitoring of U and Pu).
  - During exploration of natural resources, no unnatural material stream should go into the environment (e.g. cyanide in mines exploitation).
  - Material streams that have to leave the plant should not go into the environment unless they form a known and controlled steady state with incoming streams from the environment (e.g. not accumulation of CO_2).
  - Material streams within the process plant have to be closed cycles (limited or forbidden uses CFC or PCBs).

- **Criteria:**
  - **Renewability:** contribution of renewable energy and feedstock.
  - **Waste reduction:** waste stream reduction per unit operation.
  - **Decommissioning (Desmantelamiento):** determining the long term effect of the plant.

Social Constraints

- **Principles:**
  - All the material streams to and from the process have to meet the needs of the company, the product users and other related groups, without compromising the ability to meet the future needs of all (e.g. Energy and materials from a process plant in a developing country should also be used for the benefit of the local people now and in the future).
  - The development of new plants is aimed at meeting human needs and being in constructive interaction with the existing structure and culture of its environment (e.g. sustainable production of car fuels).

- **Criteria:**
  - Desirability (Conveniencia): technology must fit into a current and future societal context (Pollution prevention, responsible care, safety, etc.).
  - Availability: technology BAT and easily accessible.
  - Flexibility: highly flexible as regards its impact on society and the level of acceptance.

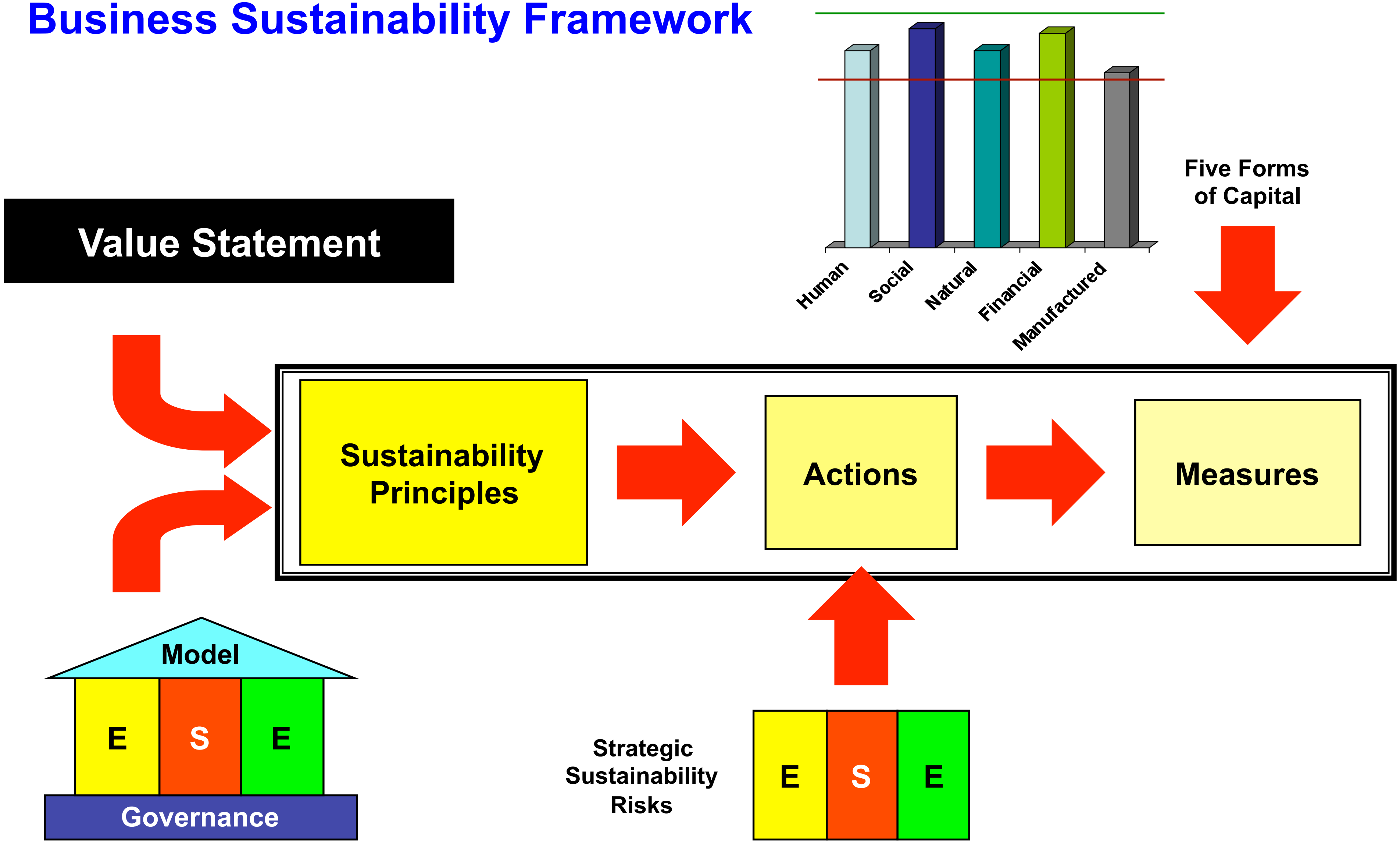
Domain Knowledge

- From the perspective of a Sustainability Design → It is important to know fields such as:
  - Green Chemistry: chemical philosophy encouraging the design of products and processes that reduce or eliminate the use and generation of hazardous substances.
  - Industrial Ecology: an interdisciplinary study of technology, society and ecology that sees industrial systems as being part of the biosphere. This is considered to be a particular case of an ecosystem, but based on infrastructural capital rather than on natural capital.
  - Waste Reduction: actions taken before waste is generated to either reduce or completely prevent the generation of waste. The combined efforts of waste prevention, reuse, composting, and recycling practices. Sometimes waste reduction is used synonymously with waste prevention.

- **LCA:** (also known as life cycle analysis, ecobalance, cradle-to-grave-analysis, well-to-wheel analysis, and dust-to-dust energy cost) is the assessment of the **environmental impact** of a given product or service throughout its **lifespan**.
- **I-O (Input-Output) Analysis:** field of economics that deals with the **connections** between **industry** sectors and households in a national economy in the form of supply and **consumption** of goods and services, formation of capital, and exchange of income and labor.
- **EIO-LCA (Economic Input-Output LCA):** approach that takes a more **aggregate** view of the sectors producing all of the goods and services in an economy.
- **Pollution Prevention (Cleaner Production):** to reduce impacts or risk of impacts to employees, local communities and the environment at large by **identifying** a problem or potential problem, locating its source within the manufacturing process, and changing the source so as to **reduce or eliminate** the problem.
  - Process modification.
  - Technology modification.
  - Good Housekeeping.
  - Input substitution.
  - On-site reuse.
  - Off-site reuse.

1.- Perspective of Sustainable Development: Sustainable Development

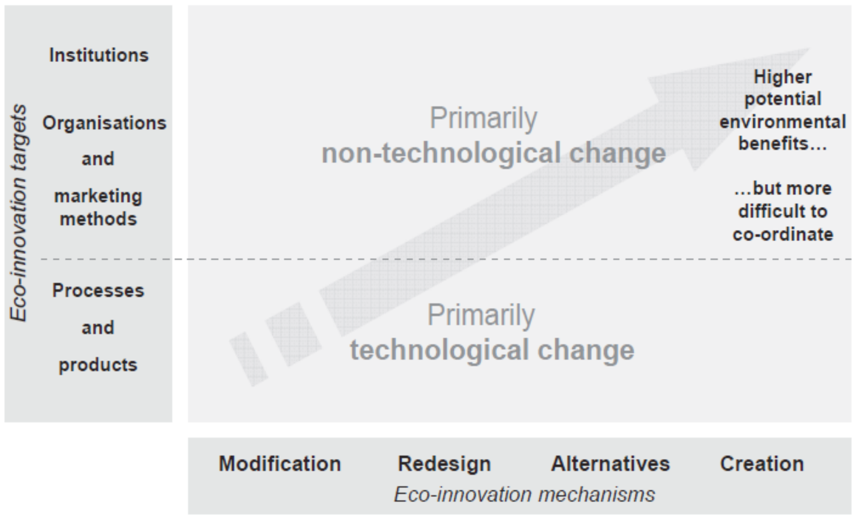
Business Sustainability Framework



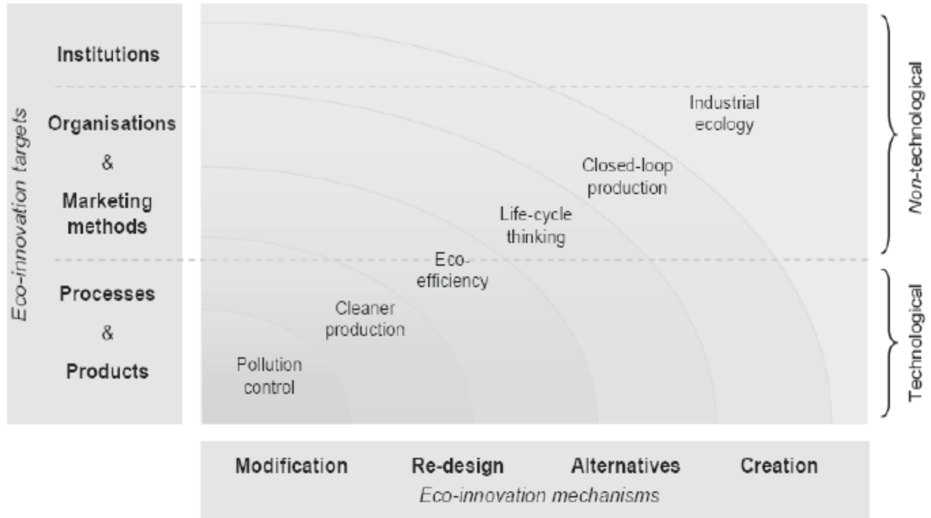
Atkins, P (2010): «Innovation for energy and the environment». 19-688; 90-821. CMU. Pittsburgh, USA.

3.- Sustainable Production, Eco-efficiency and Eco-innovation

The typology of eco-innovation

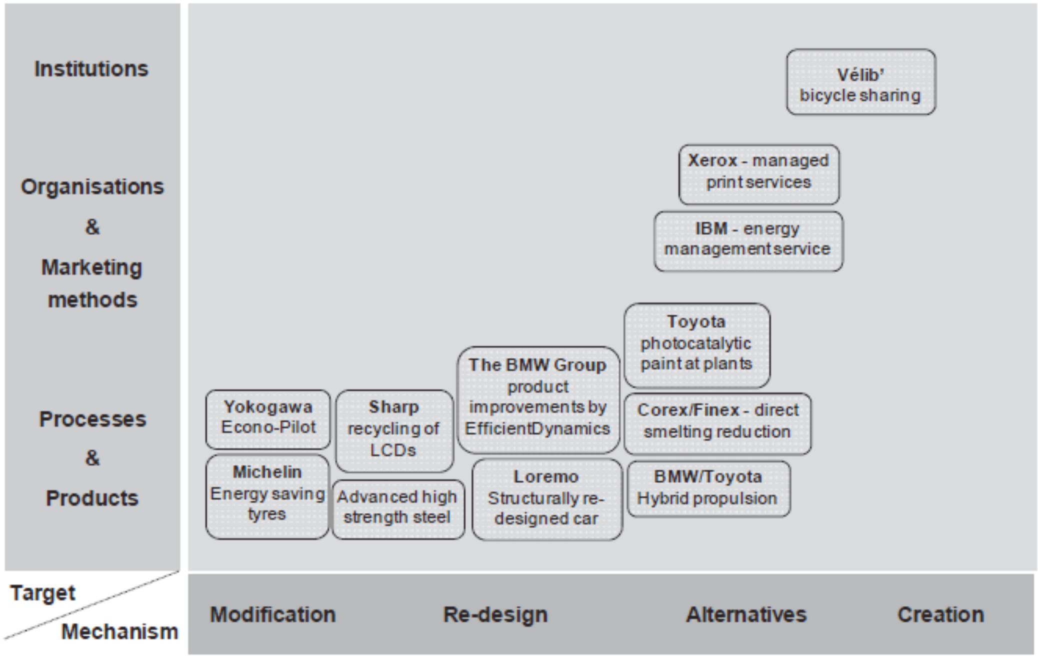


Conceptual relations between sustainable manufacturing and eco-innovation



3.- Sustainable Production, Eco-efficiency and Eco-innovation

Mapping primary focuses of eco-innovation examples



This map only indicates primary targets and mechanisms that facilitated the listed eco-innovation examples.

Each example also involved other innovation processes with different targets and mechanisms.

ECO-INNOVATION → TECHNOLOGICAL ADVANCES →

Modification
Redesign
Alternatives
New Designs

Products
Processes
Procedures
Organizational structures