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Review Paper

An Integrated System Approach (ISA) for Sustainable Development (SD) and Environmental Engineering (EE).

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Abstract: **S**ystem **T**heory (**ST**) is the best methodology to address the hot subject of **SD** and its relation to **EE** and the differences between them and to identify which is a subsystem of the other. To analyze both and their practical importance and relevance **ISA** is the best technique. In last few years **SD** has acquired special attention and specialized Journal entitled: European Journal for **SD** Research has appeared and the different aspects and applications of **SD** are being addressed and many research projects are being funded regarding **SD** research. In this paper both **EE** and **SD** are discussed from a Chemical Engineering point of view utilizing **ST** and **ISA**.

Keywords: Integrated System Approach, Sustainable Development, Environmental Engineering.

1 Introduction

Chemical engineering which is a very rich discipline by its nature have witnessed considerable expansion in the last three decades which is consistent with the Amundson report [1] and other investigations, e.g.[2]. The most successful departments in the USA and Canada as well as most of the rest of the world have been those that expanded in the direction of becoming **C**hemical and **B**iological **E**ngineering (**CBE**) Departments;(e.g.: University of Colorado, Boulder, Colorado, USA; University of British Columbia, Vancouver, Canada; Iowa State University, Ames, Iowa, USA; University of Alabama, Tuscaloosa, Alabama, USA, Department of Chemical and Biological Engineering, Rensselaer Polytechnic Institute, Troy, New York, USA ; Department of Chemical and Biological Engineering, Tufts University, Medford, MA, USA, etc.**)** with biological engineering meaning biochemical and biomedical engineering. Very similar names are, of course, also included in this category (e.g.: Division of Chemical and Biomolecular Engineering, School of Chemical and Biomedical Engineering, Nanyang Technological University, Singapore ; Chemical and Biomolecular Engineering Department, University of Houston, Houston, Texas, USA; Chemical and Biomolecular Engineering Department, University of Notre Dame, Notre Dame, IN,USA, etc.). Other departments went half the way and became departments of Chemical and Bio-Chemical Engineering only (e.g.: Department of Chemical and Biochemical Engineering, Rutgers University, Piscataway, NJ,USA; Department of Chemical and Biochemical Engineering, University of Maryland Baltimore County, Baltimore, MD,USA; Department of Chemical and Biochemical Engineering, The University of Western Ontario, London, Ontario, Canada, Chemical and Biochemical Engineering Department, Instituto Tecnolo´ gico de Veracruz, Veracruz, Ver. , Mexico; etc.) and all these departments did reasonably well. Some Chemical and Biochemical Engineering Departments split into two separate departments (e.g.: University College, London University, London, UK) and both are doing reasonably well. Other departments became departments of Chemical and Materials Engineering (**CME**) (e.g.: Department of Chemical Engineering and Materials Science, Michigan State University, East Lansing, Michigan, USA, etc.) and others became Chemical and Environmental Engineering (**CEE**) (e.g**.** The Department of Chemical and Environmental Engineering, University of Arizona**,** Tucson, AZ, USA**,** etc.) and did also reasonably well. It will be a great success to have all 4 disciplines (Chemical, Biological,

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Materials and Environmental Engineering) in one department and also to include the new comers discussed later and using a new approach suitable for such a **C**ross-**D**isciplinary (**CD**) rich new specializations. In the next few decades it is expected that **SD** engineering will become an important subs-section of some chemical engineering departments and some universities will witness the birth of **SD** departments including the **SD** engineering subsystem and other **SD** subsystems. Another new comer will be Nano-technology which will transform quickly into Nano-engineering in the same manner that Chemical Technology transformed into Chemical Engineering in the last century [3].

The components are all **E**ngineering **D**isciplines (**ED**s) and using the new approach will make them fall well under the same umbrella. However the **CD** approach extends to include not only **ED**s but also other scientific disciplines such as chemistry, physics, mathematics, microbiology, etc. as well as other social disciplines such as economics, politics, sociology, etc. This in addition to the new comers discussed below will make the graduates truly ready for **CD** jobs in industry as well as for research work in academia and industry as well as governmental research centers. It is also important to emphasis the fact that the new engineering era requires that graduates be prepared not only for design and operation, but also for innovation and should not be taught to learn only as while in school and university but also to be taught the culture, ideology and philosophy of **L**ong **L**ife **L**earning (**L3** according to the **ABET** terminology). With all this branching, interaction and synergy between disciplines and these new requirements of modern industry and the healthy forms of globalization a new approach based on **ST** and may be called **I**ntegrated **S**ystem **A**pproach (**ISA)** should be adopted both in under-graduate and post-graduate teaching and research in academia and will naturally spread to industry and governmental research centers.

The disciplines mentioned above are relatively well defined and discussed in the literature and the reader can be referred to excellent references for this purpose [1-4]. This does not mean that the last word has been said with regard to these disciplines, but it means that they are matured enough to be considered as given in a paper like this introducing some, may be, new and useful principles to this continuously expanding and complicating field. The first question now is: who are the new comers/ and are they really new comers or intelligent extension of existing disciplines? These relatively new comers are: **S**ustainable **D**evelopment **E**ngineering, (**SDE)** which is a subsystem of **S**ustainable **D**evelopment (**SD**) as a whole system [5]. In terms of **ST** and the **ISA**, we can consider **SD** itself as a system formed of technical and non-technical subsystems and **SDE** is a subsystem of the technical subsystem as shown in some details later. This relatively new comer is an extension of **E**nvironmental **E**ngineering (**EE**) which is itself an extension of **E**fficient **E**ngineering (**EE**' the dash is to distinguish it from **EE**). In other words if **SDE** (which is a subsystem of the technical subsystem of **SD**) is a system then **EE** is a subsystem of it and **EE** is a subsystem of **EE**'. While in the terms of stability theorem **EE**' can be considered necessary but not sufficient for **EE**, what makes it sufficient is the introduction of **E**nvironmental **R**egulations(**ER**s) which came into the picture in the last 4 decades only in some countries while other countries did not introduce it in a proper manner affecting negatively the rest of the world. Similarly **EE** is necessary but not sufficient for **SDE** (which is itself necessary but not sufficient for **SD**) what makes it sufficient is the introduction of **R**enewable **R**aw **M**aterials (**RRM**s) to replace the Non-**RRM**s. This brings into the picture not only **B**io-**F**uels (**BF**s) from wastes and energy crops (and not from food) and micro-algae, but also **I**ntegrated-**B**io-**R**efineries (**IBR**s) since societies do not live only on fuels. This will be made clearer later. **Fig.1** shows a diagram for **SD** and its subsystems.

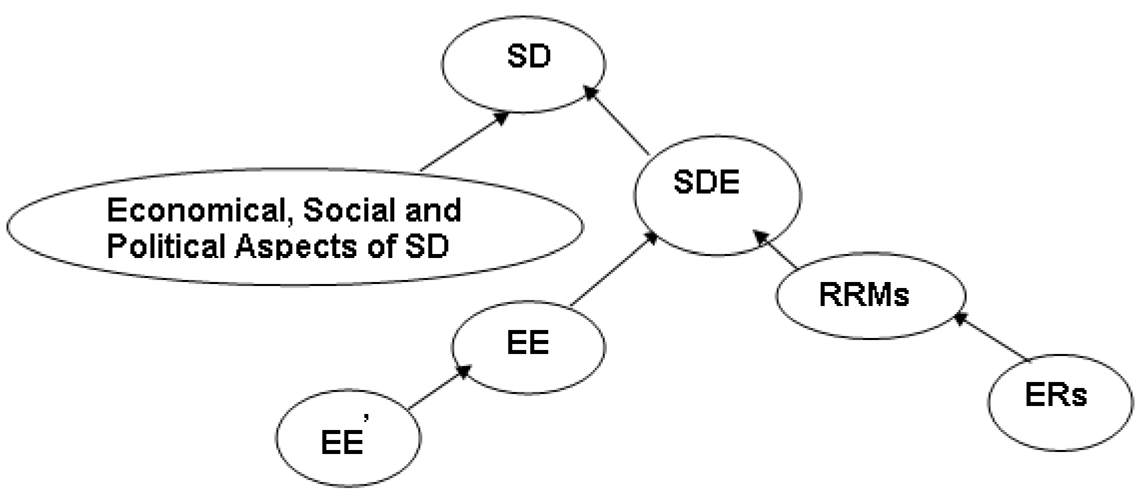

Fig.1: Simplified Diagram for SD and its Subsystems based on ST.

Main Components of SD

1- Political: e.g., legislations and strategic decisions....
2-Economical: e.g., investment in novel new technologies
3-Social, Ethical/Moral: e.g., consumption trends, acceptance of novel clean technologies and products, moral/ethical factors
4-Technological: e.g., novel efficient clean technologies, clean fuels, efficient utilization of renewable feed-stocks , new environmentally friendly products, In-process Modification for **M**inimum **P**ollution **M**aximum **P**roduction (**MPMP**), efficient waste treatment.

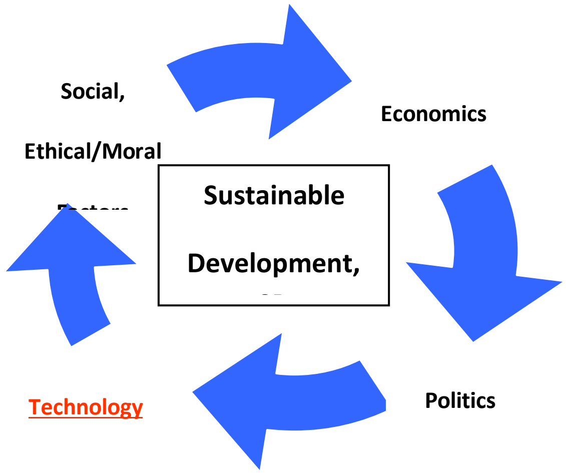

Fig.2: Another more detailed classification of SD.

Another relatively new and very important comer is **N**ano-**T**echnology (**NT**), again using **ISA**, **NT** is an advanced part of materials science/engineering, but can **NT** develop without **CD** research including physicists, chemists, electrochemists, etc.? the answer is no and it is actually an advanced system formed of many subsystems and a discipline strongly cross-linked to many other disciplines. Nanotechnology has many applications in a wide range of fields and human activities [3].
Another relatively new comer is the practical implications of **N**on-**L**inear **D**ynamics (**NLD**s), **B**ifurcation (**B**) and **C**haos(**C**). These are actually very old disciplines, some philosophers considered them as old as the great French mathematician Poincare [6-8] or even older while other philosophers consider it as old as the great Persian poet **Omar-El-Khiam [**9**]** , both are right in a way. What is really new and challenging is the practical implications of **NLD, B** and **C** especially in **CBE** systems, not because these are the richest systems in **NLD, B** and **C** but because they are the systems that the author knows more about [10-21]. **NLD , B and C** are enriching **Chemical and Biochemical Engineering Systems (C&BCESs)** and at the same **(C&BCESs)** are enriching **NLD, B and C** by introducing new phenomena**. Complexity** (**COMP**) is also quite important and it does not mean only numerical/computational **COMP**, but other forms of **COMP**, e.g.: simple configurations having **COMP** behavior and **COMP** configurations having simple behavior, and a simple configuration transforming into a **COMP** configuration through chemical and /or biochemical reactions [22]**.** It is also important to realize that **COMP** is strongly related to **NLD, B** and **C** and will be kept under this category. This paper will address a part of the tip of this iceberg, in an organized manner to be as useful as possible for other researchers to develop the ideas much further. The tools are from **ISA** based on **ST**. The objective is a systematic organized framework relating: **CBE, ME (M**aterials **E**ngineering**)** and **EE** together with the relatively new comers of: **SDE**, **NT** and practical implications of **NLD, B** and **C**.

The main tool for analysis is **M**athematical **M**odeling (**MM**) which transforms the physico-chemical system into equations. Usually the equations are non-linear because most chemical and biochemical reactions are non-linear, therefore the equations describing the systems are usually solved numerically to obtain the outputs for certain inputs and the model is verified against experimental or industrial results [9]. The input-output results are analyzed using **ST** and the **ISA**. It seems reasonable to start by **ST** and **ISA** since they are the main tools. **ST** is the basis of the **ISA** which is the most efficient methodology for classification, organization and transfer of knowledge [6] and [7] ; [23] and [24]. The approach of **ST** is very valuable in both research and education. In research, it is one of the most important components for the development of new knowledge and novel processes, especially in areas where **CD** research and development is a must for innovative solutions. **SD** is one of those areas which are **CD** by their very nature as briefly discussed above and will be discussed in some more details later on. The theme of this part is not to stress only the importance of the **ST** when dealing with the issue of **SD**, **BF**s and **IBR**s but also to use it in developing the **ISA** as a tool for investigating and discussing all issues mentioned above including the **CD** educational methodology. It is also related to **MM** the main tool for **C**omputer **S**imulation (**CS**) and the maximum exploitation of Digital Computers (**DC**s) in education, research, innovation and optimal operation and control. **ST** is shown to be the best approach to organize knowledge and transfer it in an organized and easy manner. By this we believe that **ST** is the basic tool for dealing not only with **SD** but also to be widely used in engineering education, research and industry in relation to society. A definition of some important terms in **ST** is essential to build on towards **ISA.**

2.1 System Theory (ST)

What is a system? The word system derives from the Greek word "systema" and means an assemblage of objects united by some form of regular interaction or interdependence. The main difference between **ST** and Set Theory (**ST**' to distinguish it from **ST**) is that in **ST** there is synergy between the subsystems while in **ST**' we are dealing with "dead" sets formed of "dead" subsets where the set is simply the addition of the subsets with no synergy or in other words no new characteristics which do not belong to the subsets. This is not the case with regard to systems and subsystems. A simpler more pragmatic description regarding systems includes:

- A system is a whole composed of parts (subsystems or elements)
- The concepts of a system, subsystems and elements are relative and depend upon the degree of analysis. For example, we can take the entire human body as a system, while the heart, arms, liver, etc. are elements. Or we can consider any of these elements as the system and analyze it in terms of smaller elements (or subsystems) and so on. In the other direction we can consider a country as a system and its cities as subsystems and the people as subsystems of the subsystems and the parts of these humans as elements if the analysis stops at this level or subsystems if the analysis continues.
- The parts of the system can be parts in the physical sense or they can be processes. In the physical sense the parts of the human/animal body or of a chair form a system. On the other hand, for chemical equipment performing a certain function, we can consider the various processes inside (within the boundary) of the system as elements which are almost always interacting with each other in a complex manner to fulfill the functions of the system. A simple chemical engineering example is a chemical/biochemical reactor in which processes like reactions, mixing, heat evolution/absorption, heat transfer, mass transfer, etc. take place to achieve the goal of the reactor, which is to convert reactants/substrates to products. A system can be formed of both, i.e. different parts of the system (a reactor and a regenerator combined to form a **F**luid **C**atalytic **C**racking (**FCC)** unit, each part having a number of processes taking place within its boundaries and the different parts are interacting through catalyst circulation and in each vessel the different processes are interacting and all types of interaction are giving the overall characteristics of the **FCC** unit [9-13] .
- The properties of the system are not the sum of the properties of its components (elements or subsystems), although they are, of course, affected by those components. Instead, the properties of the system result from non-linear interaction (synergy) between components (elements or subsystems). For example, humans have consciousness, which is not a property of any of its components (elements or subsystems) separated alone. Also, mass transfer with chemical reaction has certain properties, which are not properties of chemical reaction or mass transfer alone (for example, multiplicity of steady states, as discussed below). This shows the great difference between **ST** and **ST**' as mentioned above. **ST**' does not show such synergy, the set of numbers can be divided into the odd numbers and the even numbers subsets, the addition of them gives the set of numbers without any synergy unlike the **ST** which relates more to physico-chemical systems and shows that one plus one is equal two only in arithmetic.

The state of the system and state variables

The term "state of the system", rigorously defined through the state variables of the system, is used extensively. These state variables are chosen according to the nature of the system and the utilization and/or manipulation of them.

The state of a boiler can be described by temperature and pressure, a heat exchanger by temperature, a non-isothermal reactor by the concentration of the different components and temperature, an isothermal absorption tower by the concentration of different components on different plates, a human body by blood pressure and temperature, flow through a pipe by the axial and lateral profiles of local velocity and pressure. Thus state variables are variables that describe the state of the system.

Input variables (parameters)

They are not state variables. Instead, they are external to the system but affect the system, i.e. "work on the system". For example, the feed temperature and composition of the feed stream to a distillation tower or a chemical reactor or the feed temperature to a heat exchanger are input variables. They affect the state of the system, but are not affected by the state of the system (except when there is a feedback control or a recycle, in which case we distinguish between control variables and disturbances or input variables). Of course, this again depends upon the level of analysis, or the boundary of our system (subsystem), for in many cases these input variables to our system are outputs (or state variables) of a previous system (subsystem).

Design variables (parameters) :

They are associated with the design of the system and are usually fixed. Examples are the diameter and height of a **C**ontinuous **S**tirred **T**ank **R**eactor (**CSTR**) or of a tubular reactor.

Physico-chemical variables (parameters) :

They are the physical and chemical parameters of the system, e.g.: viscosity, mass and heat transfer coefficients, equilibrium constants, reaction rate constants, etc.

Boundaries of System

As encountered above, a system has boundaries distinguishing it from the surroundings or environment. The relation between the system and its environment leads to one of the most important and fundamental classifications of systems:

a- **Isolated System:** It does not exchange matter or energy with the surroundings. It tends to the state of thermodynamic equilibrium (maximum entropy). An example is a batch adiabatic reactor.

b- **Closed System:** It does not exchange matter with the surroundings, but it does exchange energy. Such a system, again, tends to thermodynamic equilibrium (maximum entropy). Batch non-adiabatic reactors are typical examples.

c- **Open System:** It exchanges matter and energy with the surroundings. (notice that exchange of matter automatically implies exchange of energy). It does not tend to thermodynamic equilibrium but to steady state or what should better be called a “stationary non-equilibrium state”, characterized by minimum entropy generation. A **CSTR** is a lumped example (state variables are not changing with the space dimension(s)), whereas a **T**ubular **C**ontinuous **F**low **R**eactor **(TCFR)** is a distributed example (state variable are changing with the space dimension(s)). It is important to notice that open systems belong to the category of dissipative systems discussed below.

Flow systems are usually open, with one or more fluid streams entering and discharging from the boundaries. However, mixing vessels and flow loops can be closed systems, with energy transferred across their boundaries (e.g. by impellers of pumps) to provide the energy needed to initiate and maintain the motion, most or all of this energy ultimately being dissipated due to viscosity.

The above shows that the term “steady state” commonly used in **CBE** is not really very accurate, or at least it is not precise enough. A more accurate phrase should be **“stationary non-equilibrium state”,** which is a characteristic of open systems, distinguishing it from **“stationary equilibrium state”,** associated with isolated and closed systems.

Steady, unsteady states and thermodynamic equilibrium of systems

As briefly stated above, the **steady state** (**stationary non-equilibrium state**) is a concept related to open systems (all continuous **CBE** processes are open systems). **Steady state** occurs when the state of the system stops changing with time, but the system is not at thermodynamic equilibrium, i.e. the processes inside the system do not stop and the stationary behavior with time is due to a balance between input, output and processes taking place within the boundaries of the system. This steady state of lumped systems is a point in a space having the same dimensions as the problem (number of components + temperature + pressure, etc.), whereas that for distributed systems are profiles in the space co-ordinate(s) as additional dimension(s). **Unsteady state** of an **open system** starts at an **initial condition** and tends with time towards a **steady state** when the system is **stable** (a point for lumped system and profile for distributed systems). This initial condition for lumped systems is a point in the space dimension of the problem, while for distributed systems it is a profile in the space co-ordinate(s) as additional dimension(s). What if the system is unstable? This is addressed in a later section about **NLD, B, C and COMP.** On the other hand, for **isolated and closed systems** the unsteady state changes with time, tending towards thermodynamic equilibrium, which is stationary with time because all processes have stopped (the process is “dead”).

For flowing systems (leaving aside ideal, i.e. in viscid, fluids and fluid static), energy is required to actuate fluid motion and maintain steady flow and transport processes. If the source of energy (e.g. a pump, potential energy, or a heat source) is terminated or exhausted, then the system asymptotically approaches the thermodynamic equilibrium state of a static isothermal system.

2.2 Integrated System Approach (ISA)

The current lack of success in improving industrial sustainability, coupled with the challenges of bio-complexity and resilience, indicates that sustainability is a system’s problem requiring collaborative solutions with **CD** nature.

Other issues introduced in the introduction follow the same route. A number of technical advances will likely improve the usefulness of models, including rigorous methodologies for dealing with missing and uncertain information; improved methods for interpretation of multivariate data sets and for multi-objective decision making involving trade-offs among conflicting goals; and novel modeling methods as alternatives to traditional **MM**. More generally, there is a great need for operational definitions and metrics for sustainability and resilience in economic, ecological, and societal systems. **SD** in a changing global environment will require resilience at many levels, including human communities and economic enterprises. In the face of ever-increasing global **COMP** and volatility, it is essential to move beyond a simplistic "steady state" model of **sustainability**. Instead, we need to develop adaptive policies and strategies that enable societal and industrial institutions to cope with unexpected challenges, balancing their need to be able to achieve efficient **sustainable BF**s as one of the many challenges imposed by modern industry and societies and reflecting themselves upon education, industry, research and the entire society in a global manner. **ISA** is the use of **ST** to tackle all these challenges in an integrated, efficient and well organized manner. **ISA** utilizes **MM** and **CS** to the highest level coupled to experimental work and organized exploitation of industrial data not only to improve operation but to discover novel processes. It maximizes utilization of present technologies using on-line efficient computer optimization and control with objective functions being not only **M**aximum **P**roductivity but also **M**inimum **P**ollution (**MPMP**). It does not stop at that; it also considers conceptual optimization which may change the technology fundamentally, i.e.: from fixed bed to fluidized bed by Grace and co-workers in **U**niversity of **B**ritish **C**olumbia (**UBC**) [25-27,32] and Elnashaie and co-workers [5,9,19,24] and many others; using membranes to "break" thermodynamic equilibrium barriers for reversible reactions and integrated membrane reactors having complementary reactions at both sides of a suitable membrane by Elnashaie and others [28-35] ; as well as combining endothermic and exothermic reactions to achieve an auto-thermal process by Elnashaie and others as given for example in the above references ; a continuous reactor-regenerator process such as **F**luid **C**atalytic **C**racking (**FCC**) [9-13; 36 and37] and its continuous development by petroleum companies, **P**ressure **S**wing **A**dsorption (**PSA**) to replace absorption-regeneration , **P**inch **T**echnology (**PT**) for maximum energy efficiency in **H**eat **E**xchangers (**HE**s) **N**et **W**orks (**NW**s) and its extension to **M**ass **T**ransfer (**MT**) **NWs** by El-Halwagi and co-workers at **UCLA, Auburn and Texas A&M [38]) ,** novel polymerization processes such as the fluidized bed **UNIPOL** process for polyethylene and polypropylene polymerization and their further developments [39] and also the bifurcation and chaotic characteristic of these and other polymerization reactors by Ray, Teymour and others at Wisconsin, Madison and **I**llinois **I**nstitute of **T**echnology (**IIT**) [40-43] . The list is endless and efforts toward novel designs using conceptual de-bottle-necking are intensifying in academic research, research centers and industry**.**

3 Advanced CD Engineering Education

Now after briefly introducing the **ST** and **ISA** concepts we move to Engineering Education, not only with regard to **CBE** education and its branching but also with respect to Engineering Education as a whole with special emphasis on **CBE** and its **CD** branching [41-43] . In the last two decades Engineering has been quickly entering a new phase. The speed of transformation has been accelerating and the boundaries between different engineering disciplines are falling down very fast [44-51]. In addition, the boundaries between engineering, with its different specializations, and other scientific disciplines (chemistry, microbiology, mathematics, etc) are becoming more permeable. Also the engineering disciplines are becoming more integrated to socio-economic, political and moral/ethical issues. In addition the world economy is moving from national economies with continuously intensifying exchange to a global economy which is much more integrated and competition is more intensive. Moreover, awareness of the danger of depleting the non-renewable resources and exceeding the absorption capacity of our ecosystem is increasing. This state of affairs is calling for a radically new approach not only with regard to engineering research but also **EE**. Engineering is branching into more specializations, while at the same time is calling for closer integration between different engineering, scientific and humanitarian specializations. In addition to the four main disciplines(**CBE, M**echanical **E**ngineering **(ME) and EE**), among the new comers **SD** gave birth to **SDE** and even before fitting the other newcomers (**NT,NLD,B and C**) into the framework the situation becomes quite complex. **SDE** shows very clearly that **EE**' and **EE** are necessary but not sufficient for sustainability. We can have very efficient designs and very clean technologies but they are not sustainable because they do not use **RRM**s. Sustainability is becoming the modern focus of all research and development and the main challenge facing science and technology in the twenty first century. Research on renewable energy is very important and is intensifying both in academia and industry. This is good, but modern societies do not live only on energy, there are other products and commodities that have to be produced from **RRMs**. Here comes strongly into the picture the concept of **IBR**s which will not only produce clean renewable **BF**s but also other Bio-products and Bio-commodities.

When we add up the above 4 basics and 3 newcomers we have a huge engineering building attached to all other engineering and scientific disciplines. This huge **CD** engineering complex has its foundations based on fundamental knowledge; technological progress is limited by these foundations. Therefore fundamental research is extremely important in this challenging and interesting episode for the good of the entire world. The link between scientific discoveries and technological innovation through transformational engineered **ISA** is becoming very important.

These challenges call for a **CD** research involving all types of the continuously evolving human knowledge. This **CD** research is evolving continuously and will create new ideas and innovative breakthroughs not expected before. This challenging and promising new trajectory needs a tool to help organize it and bring it to useful and dynamic conclusions. The **ISA** based on **ST** both discussed above are the best tools for the generation, organization and transfer of knowledge with positive synergetic effects maximizing the return on investment for research and development.

3.1 Sustainability and Profitability

There are strong evidence that there is some contradiction between sustainability and profitability **s**ome researchers are even claiming that there is a contradiction between sustainability and the second law of thermodynamics**.** The most suitable solutions to these contradictions are through innovation which is, from an informatics point of view, a very good source of negative entropy. From the above brief introduction we can clearly point to the following general needs of modern advanced economies and societies as briefly given below:

a) Develop a culture of **D**iscovery and **I**nnovation (**D&I**) through the entire education/research system with special emphasis on engineering education and research.
b) Find **I**nnovative **S**olutions (**IS**s) for the contradiction between sustainability and profitability.
c) Develop an efficient approach for linking fundamental scientific discoveries to engineering applications, **E**fficient **S**cience to **T**echnology (**EST**). The best such approach is an integrated **CD** approach based on **ST**.
d) Develop among the different generations of engineers a strong spirit of entrepreneurship and the development of high-caliber engineers with strong **CD** capabilities suitable for leadership in a global economy. This includes developing among undergraduate and graduate students the creative process and cross-cultural collaboration. The pre-college education including institutes, teachers and students is also an integral part of this process.
e) Expanding the use/development of **MM**, **CS** computer and optimization techniques.
f) Expand the domain of **EE** which aims at clean technologies to **SDE** aiming at **SD**.
g) Develop an engineering awareness of the technological implications of global economy in order to produce engineers and researchers able to define pathways to sustainability coupled to high profitability.
h) Successfully explore/realize innovation opportunities and becomes qualified to be in the forefront of competition in a global economy.

i) Develop strong relations between, academia; small innovative firms; relevant large agricultural and industrial producers as well as federal, state and local authorities. These relations should be aiming at intensifying discoveries, innovation and their commercialization nationally and internationally. This will include not only **CD** research and development but also education and continuous training.
j) In a global economy, teaching, research, design and production cross national borders calling for the development of partnership with foreign universities, research centers and industries for teaching, training, research co-operation and innovation in a global economy. Develop different categories of **CD** engineering departments each one involving an optimally chosen number of disciplines in order to achieve an integrated **CD**

Operation. These departments should be formed of diverse and talented domestic and international individuals who will prepare diverse talented individuals who can function in global economy, where design, production and innovation efforts across national borders.

Different engineering departments are needed with different engineering disciplines in order to achieve a good step forward in the arena of strong competition in a growing global economy.

The framework of the above 10 general characteristics (summarized in Fig.3) is essential for starting a successful **CBE** department including the 4 well established disciplines in the right way and also encompassing the 3 main new comers. The department will have the components of the typical present **CBE** departments classified on the basis of ISA as follows in addition to necessary fundamental subjects such as chemistry, biochemistry, mathematics, physics, computer programming and humanities. This will mainly include:

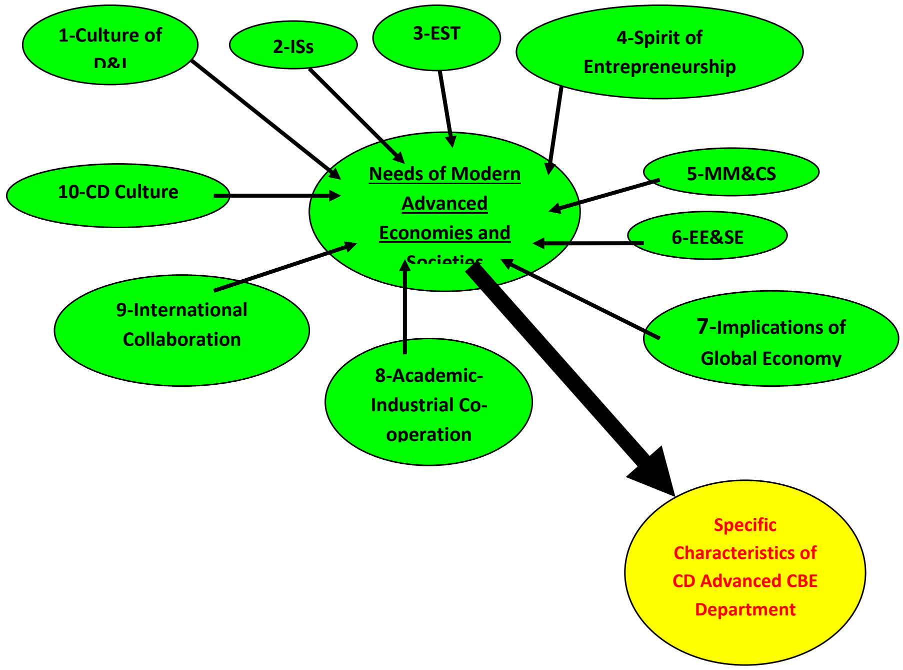

Fig.3: 10 needs of Advanced Economies and Societies and output to a CBE department.

I. Material/energy balances for chemical/biochemical reacting/non-reacting systems.
II. Transport phenomena.
III. Mass Transfer.
IV. Heat transfer.
V. Sizing of reacting and non-reacting chemical and biochemical system.
VI. Process control for reacting and non-reacting chemical and biochemical systems.
VII. Momentum balance; momentum transfer and fluid dynamics.
VIII. Plant design and economics.

In addition to the classical components , condensed and organized using an **ISA**, such a department will have special emphasis regarding research and education on the points shown below and condensed in Fig, 4 with the outcome of Fig 3(the green box in Fig.3) as an umbrella:

BFs: including developing and optimization of novel efficient compact processes and comparing them as renewable energy sources. A good preliminary plan is to concentrate on:

- Cellulosic Bio-ethanol using different feed-stocks and different processes, e.g.: Lignocelluloses fractionation followed by hydrolysis of cellulose/hemicelluloses; followed by fermentation. The emphasis should also include bio-butanol because of its advantages over bioethanol. Novel processes, novel modes of operation as well as novel mutated microorganisms will be combined to exploit the positive synergies between these factors to achieve highest possible efficiency. **C**ontinuous **S**tirred **T**ank **F**ermenters (**CSTFs**) as well as packed bed immobilized fermenters are to be considered. Different hydrolysis techniques should also be considered, both acidic and enzymatic, to reach the most efficient route for sugars production from cellulose/hemicelluloses. In the fermentation step, different techniques for continuous ethanol removal are to be considered to maximize breaking the inhibitory effect of ethanol on the fermentation process. Unusual modes of operation : Chaotic fermenter [14] is also to be explored. Novel mutated microorganisms are to be developed in collaboration with microbiologists from other departments to ferment all the types of sugars resulting from the hydrolysis step, and to be tested in classical and novel membrane fermenters.
- Bio-hydrogen, including producing it through biological processes from non-bio raw materials (e.g.: biological **W**ater **G**as **S**hift (**WGS**) of **CO** and also thermo-catalytic from bio raw materials (e.g.: hydrogen extraction from syngas produced from biomass through gasification or catalytic gasification or fast pyrolysis of biomass to bio-oil followed by steam reforming of bio-oil), or bio-processing of biomass (biological treatment of well-

chosen biomass using suitable microorganisms). Both in-situ as well as ex-situ removal of hydrogen will play an important role in the cut-edge development of these processes to make it competitive with the classical catalytic steam reforming of natural gas and its recent improvements using bubbling and circulating fluidized bed membrane reformers**.**

- Biodiesel, including the short term small scale bio-diesel from vegetable oils (or used oils) through trans-esterification using metals or enzyme catalysts and suitable alcohols. However the main thrust will be regarding the long term, large scale production of **F**ischer-**T**ropsch bio-diesel (**FT**-bio-diesel) from syngas produced from biomass through one of the processes described above. The research should compare the two routes for syngas production with special emphasis on the percentage of the valuable component, hydrogen, in the syngas. The research should concentrate on developing a novel suitable and efficient membrane **C**irculating **F**luidized **B**ed (**CFB**) process for the steam reforming of bio-oil as well as a novel **FT** process that operates at relatively high temperatures and with a syngas having a very high yield of H_2 and CO_2/CO ratio which is a characteristic of the syngas produced from the efficient membrane reformer. Research will also extend to developing a novel compact auto-thermal membrane reactor combining both the endothermic steam reforming of bio-oil and the exothermic **FT** reaction of syngas to **FT**-biodiesel. The research will also include novel ideas to improve the fast pyrolysis and the catalytic gasification processes as well as the biomass collection, classification and pre-treatment before processing. In addition the different **FT**-bio-diesels produced will go through the standard tests, including diesel engines testing and these characteristics related to parameters associated with the raw materials and novel technologies used.
  Such a department will also address in an objective scientific manner the dispute regarding **E**nergy **R**atio(**ER**) and **N**et **E**nergy **R**atio (**NER**) for bio-fuel and fossil fuels which will address the energy from quantitative as well qualitative points of view.

3.2 Efficient Energy Utilization (EEU): which includes many subjects related to both clean fuels (e.g.: hydrogen), **BF**s from **RRM**s, etc and will also include optimal clean utilization of fossil fuels. In this work it should be planned to improve the efficiency of the cleanest way to produce the clean fuel hydrogen, that is electrolysis and the cleanest and most efficient way to produce electric energy which is the fuel cells. The improvement will concentrate on biotechnology as the main focus by developing novel bio-electrolysis process and bio-fuel cells. Other techniques to improve the efficiency in the two processes and their interfaces should also be integrated with this biotechnology based improvements. Integrated electrolysis-fuel cells are used in order to achieve continuous electricity source which is necessary for certain applications (e.g.: thermally efficient housing) from an intermittent clean source (e.g.: solar energy). The efficiency of this integrated process can be improved considerably using the suggested bio-electrolysis coupled to the bio-fuel cells. Research will also include the development of this integrated process in co-operation with the designers and developers of thermally efficient housing.

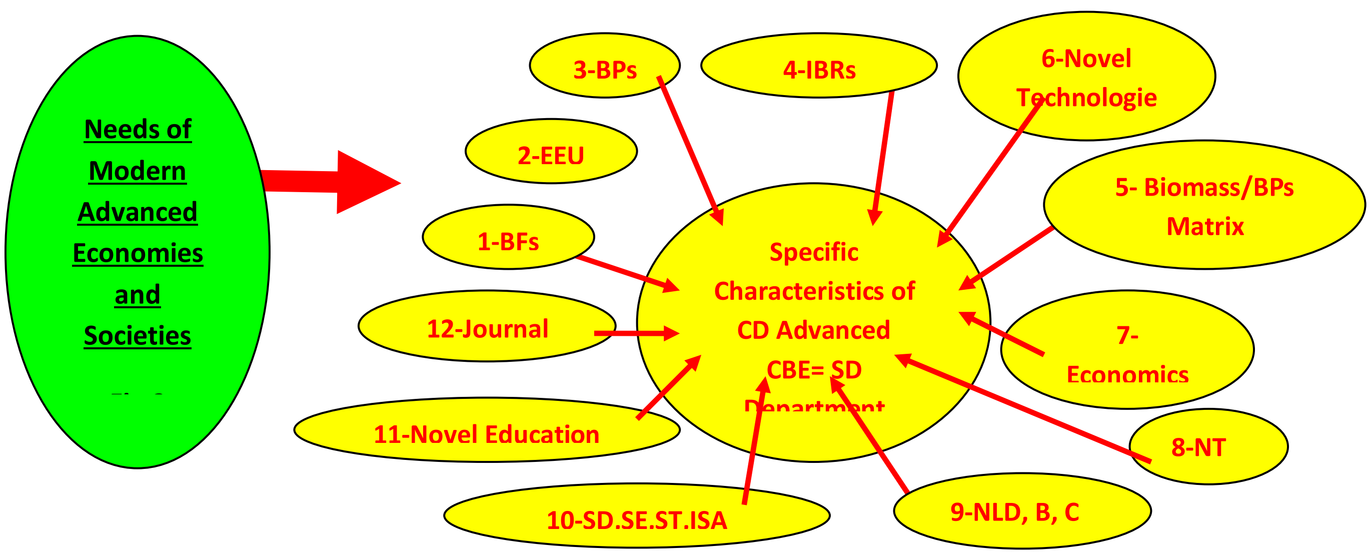

Fig. 4: Needs for Fig.3.

3.3 Bio-Products (BPs): they are very important part of **SD** due to the simple fact that, although most of the attention is going to the important subject of sustainable energy, societies do not live only on energy; there are many other commodities (consumer goods) and capital products that need to be replaced by sustainable **BP**s. Societies are alarmed about the fact that oil has passed its peak and will finish in a few decades, but what about other raw materials? In fact cupper is running short and its price is rocketing high. Thus research and preparation of engineers will not include only novel processes development, but also novel products development. The approach will depend upon the highlighting of the most critical raw materials that are dangerous to **SD** other than energy, as well as the commodities and capital products related to those raw materials coupled to the commodities and raw materials which are easiest to replace with replacements produced from **RRM**s. This essential classification and focusing process will be followed first by identifying the state of the available technologies related to these factors. This process will then lead to the most important novel processes and products to develop and to establish the research program to develop them efficiently and cleanly.

3.4 IBRs: it is a concept which is still at its infantry. Relatively recently **NSF** has offered a solicitation for the development of **IBRs** which will be the tool, in the near future, to achieve the above points in an integrated manner that is producing **BFs** and other **BP**s in one **IBR.** In order to have a clear vision of **IBRs** it is essential to realize what a **BP** (or **BF**) is? It is any product produced from a biological process even if the raw material is not a bio (e.g.: hydrogen from **CO** using biologically catalyzed **WGS** process). It is also any product produced from a bio-raw material using non-biological process (e.g.: biomass to bio-diesel using any technique for the production of syngas followed by **FT** process). It can also be both, i.e.: the raw material and the process are both bio (e.g.: Cellulosic waste to cellulosic bio-ethanol through a number of steps most of them are bio-processes). Beside biomass and other forms of wastes there is also special crops which are being developed to be used for **BF**s and other **BP**s (e.g.: switch grass). In addition there are very important bio-raw materials which are treated now as waste or cheap fuels such as lignin which is separated from different types of lingo-cellulosic wastes (especially agricultural waste such as rice straw). Through intensive innovative **CD** research this lignin can be a base of a part of **IBRs** to compete, and eventually replace, the present petrochemical industry based on none-**RRM**s. Well directed research can also produce sugars for fermentation to ethanol from this lignin waste which will increase the yield of the cellulosic bio-ethanol process more than 30%. It is also important to recognize the meaning of **RRM**s, this is very relative, for, theoretically speaking, fossil fuel is also renewable, but its cycle is a million years or more. So what we mean by renewable raw materials is a raw material which is renewable over few months up to a maximum of a couple of years. We should also add that its **L**ife **C**ycle **A**nalysis (**LCA**) should show a net $\mathbf{CO_2}$ (and any other harmful side product) of almost zero, i.e.$\mathbf{CO_2}$ produced is consumed in photosynthesis to produce almost the same amount of renewable raw materials. The socio-economic implications of **IBRs** will include both production and consumption sustainability. Research should address, in a **CD** integrated manner, all technological, socio-economic, political and moral/ethical aspects. **IBRs** are formed each of at least two platforms, the most developed is the one with biochemical platform and a thermochemical platform, a bio-refinery with one platform is not an **IBR** but an Elementary Bio-Refinery(**EBR**).

3.5 Biomass/ BPs Matrix: Other efficient utilization of **RRMs** especially biomass, although the above bio-energy and other bio-products represent the core of biomass utilization for **SD** other utilizations are possible. Bioprocesses are very location sensitive and vary very widely from one place to the other and even with the change of circumstances in the same place. For example, in some places some kinds of biomass will optimally be used for the production of composites for the agriculture soil, in other places it will best be used as an addition to buildings materials, etc. Some animal residues also can have either general applications in production of **BF**s and **BP**s or special applications for special products or services. This part of the research and education should involve a classification of the different types of biomass, their geographical availability within the US, Canada or any other country around the world together with the different products possible from the different types of biomass. It should be a matrix of biomass **RRM**s as columns and possible products as rows with the technology suitable for each element of this matrix corresponding to a certain **RRM** and a corresponding product. It will be shown later that an **IBR** will occupy a certain part of the matrix or the entire matrix. It is also important to realize that each such matrix element does not correspond to a single technology relating the specific **RRM** to the specific product. Therefore the process will also include surveys of the existing technologies to produce these products from these categories of biomass and the needed novel technologies to achieve that when no technology is available or the available ones are not efficient or not environmentally friendly. Research and education will also address the non-technical factors associated with the choice of the optimal products and optimal processes from specific types of biomass with special emphasis on the characteristics of the locality of the specific biomass.

3.6 Development of Novel Technologies: this is to be achieved through different intellectual innovation processes, e.g.: sequential de-bottlenecking. The process of developing novel technologies is much more difficult than optimizing and improving the efficiency of an existing technology and both are important. This is due to the

fact that in the last few decades lots of very efficient, modeling and computer tools has been developed to efficiently achieve the optimization of existing technologies. However the development of novel technologies takes lots of intelligent, intellectual efforts and development on the basis of a culture of discovery and innovation which is not strong enough in our present educational system. Innovation includes both novel configuration (e.g.: efficient fluidized bed membrane steam reformer for hydrogen production instead of the inefficient present fixed bed reformer constrained by thermodynamic equilibrium limitations+ intra catalyst particles diffusional limitations + heat transfer limitations) and novel modes of operations (e.g.: periodic or chaotic autonomous or non-autonomous processes leading to higher yields and productivity compared with optimal steady states). It may also involve a novel product or service. The suggested center will work hard to become a focal point not only for developing specific novel technologies but also to develop the culture of discovery and innovation and to develop all possible intellectual tools for this process, e.g.: sequential de-bottlenecking.
In addition, novel configurations usually have more complex configurations than classical configuration (e.g.: **CFB** membrane reformer compared with fixed bed reformers). This gives rise to mechanical and hydrodynamic challenges which will be tackled in the center both experimentally and using advanced computer modeling and simulation.

3.7 Economics of BFs and BPs: making these bio-processes and bio-products economically competitive, socially acceptable, sustainable and environmentally friendly as well as gaining political support for it, certain steps need to be taken into consideration. The main bottleneck for bio-fuels and bio-products is certainly economics. The main challenge is to break the contradiction between sustainability and profitability, in other words to present to the consumers products which are reasonably priced and for the producers (and the rest of the production-consumption chain) products to achieve reasonable profit for the economic cycle. However, and despite the major importance of economics, other social, political and moral/ethical factors are not negligible at all. All the factors contribute to the success of achieving sustainable economy which is also clean and leads to peaceful co-existence between peoples. The center will use a system approach in order to study the positive and negative synergy between these different factors associated with sustainable development and its relation to **BFs** and **BPs.**

3.8 Nano-Technology (NT) [3]: addressing this hot new comer in a **CD** manner and its applications in all fields of applications, especially chemical and biological engineering applications. This field opens new horizons in all applications and is multidisciplinary by its very nature. This new department will be the best focal points for the development of this strategic field in co-operation with other engineering and science departments.

3.9 NLD, B and C [9]: this field (system) is usually considered to belong to the theoretical part of knowledge and investigation. However in the last three decades these phenomena are finding more practical applications and relevance both for autonomous systems as well as non-autonomous systems. They are important to understand many phenomena which are not possible to understand them without having the fundamental knowledge associated with this field. All systems are actually non-linear and therefore there dynamics lend themselves to this field, linear system are actually approximations obtained by linearizing the system in the neighborhood of a specific state and therefore gives local characteristics but not global ones. Bifurcation has dismantled the boundaries between static and dynamic behavior and made them interdependent. This is a **CD** field by its very nature and is quite important to control when the behavior is harmful and exploit when it is useful. **COMP** belongs to this field and it is a very important subsystem of this system as briefly discussed above and shown later in more details.

3.10. SD, SDE, ST and ISA [52]: sustainability is still young and many of its aspects are not completely clear even among academicians. A simple example is the question, phrased on **ST** terminology, is **EE** a subsystem of **SDE** or the opposite? The preliminary believe accommodated at this time by the research group of this paper is yes it is a part of **SDE** and that **EE** is necessary but not sufficient for sustainability and that good efficient engineering is not sufficient for sustainability . This is due to the fact that you can have a very efficient, clean technology, but if it is based on non-renewable raw materials then it is not sustainable. However these concepts are still not deep enough, technologically, socio-economically, politically and from moral/ethical points of view. Even most definitions of sustainability and sustainable development are not very accurate and they are more catch-phrases than strong meaningful and survivable definitions. The suggested center will use system approach to move forward in the direction of establishing stronger, clearer and more meaningful definitions to these important concepts. This effort will help all involved as well and others to achieve all other tasks.

3.11 Novel Education: using **CD** teaching programs on the above subjects prepares the graduates for leadership positions in a global economy as innovators. As we want to shorten the period between scientific discoveries and their innovative technological application through transformal engineered systems approach, we want also to achieve the same with respect to education. This is best achieved using a new approach for engineering education based on **ST** which is the best and most efficient mean to organize and transfer knowledge and create a common language between disciplines. This is due to its very nature and its definition of systems, subsystems, their boundaries and characteristics in general terms not restricted to specific system or disciplines. It is also the best mean to make the gap between scientific/technological discoveries and teaching/training as short as possible, which is very desirable in a very competitive global economy. The center will develop new educational programs based on system theory, designed for:

a. strategically creating the capacity to initiate and exploit knowledge for technological innovation and minimize the gap between scientific/technological discoveries and education/training.
b. maximize engineers ability to think positively and independently in contradistinction to memorizing or learning engineering as a craft.
c. develop graduates experienced in the creative process and cross-cultural collaboration.
d. develop graduates able to define pathways to explore and realize innovation opportunities for success in a global economy.
e. develop graduates who are leaders in a global economy.

These educational programs will be formed of diverse (domestic and international) and talented individuals as teachers/trainers who are part of the research program of the center. They will prepare diverse talented individuals (domestic and international) who can function in global economy, where design and production efforts across national borders. Diversity will also include cross-disciplinary team of faculty members and students that is diverse with respect to gender, race, ethnicity, disability, and culture.

3.12- New Journal: last but not least a suggested department for **SD** may pioneer the publication of a modern international **CD** engineering journal. The aim of this Journal is to be one of the tools to address the bio-energy, **BFs, BPs, IBRs** and sustainability challenges and make sure of publishing and spreading widely, nationally and internationally, the novel work of the department and similar departments worldwide, as well as relevant research nationally and internationally. The journal will emphasis novel ideas and make it reach the scientific community in an efficient manner. The Journal will aim at the publication and dissemination of original research, reviews and discussions on the latest developments in the fields of **BFs, BPs, IBRs,** sustainability and their synergic relations to each other and to global economy. It will also address challenging educational issues related to innovation and developing a new generation of innovative engineers suited for the global economy. It should also focus on research utilizing **ST** and **ISA** to develop novel technologies which contribute to **SD** for the entire planet and its entire population in the framework of global economy as well as advances on the foundations of fundamental knowledge. Papers may be theoretical (including computational), experimental or both. Also intellectual conceptual ideas to advance the culture of discovery and innovative thinking should be given especial attention.

3.13 Conclusions

This is a very brief conclusions for the above 3 sections and it does not include the 4^{th} section below. In the last few years **SD** became a very hot subject addressed in all engineering and non-engineering subjects. For us as engineers its subsystem **SDE** is the most important for us however it is affected by other **SD** subsystems. **MM** and numerical solution of the model is the most important tool for **SDE** studies and research together with the other subjects discussed in the paper above. **EE** is a subsystem of **SDE** and the other subsystem is **RRM**s . **EE** and **RRM**s together formulate **SDE**. In the next few years some universities will see the birth of **SD** departments while others will see the introduction of **SD** courses to the curriculum of some departments specially engineering ones.

4 Brief on Catalytic Reactions to Maximize Production and Minimum Pollution (MPMP).

Necessary but not sufficient conditions for Sustainability

One of the main techniques for pollution control and achieving green technology is to achieve **MPMP**. Almost all catalytic reactions in the **P**etroleum **R**efining (**PR**) and **P**etro-**C**hemical **(PC**) industries are reversible and therefore their conversion is limited by the thermodynamic equilibrium. This conservative limitation can be broken by using selective membranes to remove one of the products. In this couple of pages this revolutionary concept leading to **MPMP** is used for the dehydrogenation reaction where the selective membranes are used for the perm-selective removal of hydrogen [28-35]. These membranes have 100% selectivity for the removal of hydrogen. Most efficient configuration is when in the other side of the membrane is a hydrogenation reaction and the flows in the two sides of the membrane are counter-current. Such **MPMP** for catalytic reactors is essential part of **S**ustainable **D**evelopment **E**ngineering (**SDE**) which is an important subsystem of **S**ustainable **D**evelopment (**SD**) as discussed above. The removal of one, or more, of the products relaxes this limitation and increases the conversion of the reaction; this relaxation increases as the removal of the product(s) is increased. The optimal utilization of this approach leads to **MPMP** approaching green technology and is a part of **SDE**. This short part is concentrating on the removal of hydrogen from a dehydrogenation reaction, mainly ethyl-benzene to styrene [28-35], using hydrogen perm-selective membranes. The rate of hydrogen removal from the reaction side depends upon the type of the membrane and also the hydrogen driving force between the two sides of the membranes. This driving force increases when there is a hydrogenation reaction in the other side of the membrane. In this part a hydrogenation reaction of nitrobenzene to aniline is taking place on the other side of the membranes (It can also be benzene hydrogenation to cyclohexane depending on the supply-demand circumstances). Figure 5 shows a schematic diagram for this novel integrated membrane reactor. Figure 6 shows the hydrogen profiles for both co-current and counter-current configurations. For counter-current case, feed is from the right for the hydrogenation compartment; otherwise all feeds are from the left. The counter-current is obviously more efficient.

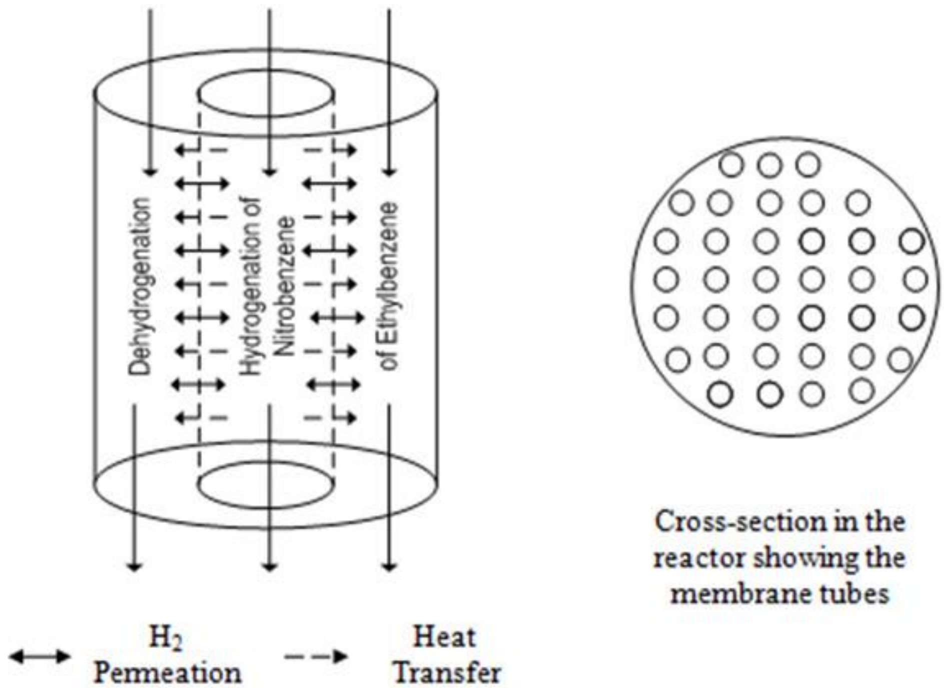

Fig. 5: Schematic diagram showing integrated reactor configuration.

5 Sufficient Conditions for Sustainability

The above is only necessary for sustainability because the raw materials are not sustainable since they are non-**RRM**s. In order to make this clean **MPMP** also sustainable it is necessary to make the raw materials **RRM**s, the easiest way to achieve that is to use biomass to produce syngas by gasification, then use the syngas to produce the **E**thyl-**B**enzene(**EB**) and the **N**itro-**B**enzene(**NB**) needed as feed stock using the **FT** catalytic reactors(e.g.:[53-55])

Regardless of the source of the raw materials , the two reactions in the membrane are mainly:

- **Dehydrogenation of EB to Styrene(S):**

  $C_6H_5CH_2CH_3$ (**EB**) $\longleftrightarrow$ C_6H_5CHCH(**S**) + H_2

It is an endothermic catalytic reaction with the shown stoichiometric numbers

- **Hydrogenation of Nitrobenzene to Aniline (A):**

  $C_6H_5NO_2$ (**NB**) + 3 H_2 $\longleftrightarrow$ $C_6H_5NH_2$ (**A**) + $2H_2O$

It is an exothermic catalytic reaction with the shown stoichiometric numbers.

The feed molar flow rates are: 10 moles/sec for **NB** and 30 moles/sec for **EB** which is consistent with the stoichiometric numbers shown above, i.e.: Dehydrogenation of one mole of **EB** gives one mole of hydrogen while the Hydrogenation of one mole of **NB** needs 3 moles of hydrogen

The hydrogen flow rate in the dehydrogenation side is the result of the difference between the hydrogen production (+) and hydrogen diffusion through the palladium membranes to the hydrogenation side(-) and therefore it has a maximum peak as shown in Fig.6, however, as expected, the peak of the counter-current case is higher than that of the co-current case. Feed reactants at both sides of the membranes are almost consumed in order for the dehydrogenation reaction to provide sufficient hydrogen for the hydrogenation reaction. Also , since 3moles of **EB** need to react to supply the necessary hydrogen for one mole of **NB** and the heat of reaction of the endothermic **EB** reaction is ΔH_{298}=117.6 KJ/mole and that of the exothermic **NB** reaction is $\Delta H_{298} = -443.0$ KJ/mole, , therefore the net exothermic heat is higher than the endothermic heat (117.6*3=352.8 KJ/mole) and the difference between exothermic heat and the endothermic heat is an exothermic heat per mole of **NB**= 90.2 KJ/mole of **NB ,** assuming that all the heat required for the endothermic **EB** reaction is transferred through the membrane from the **NB** hydrogenation side. This heat if not extracted from the system by cooling will lead to an increase of the temperature along the hydrogenation side. These very simple calculations and results are based on the very simplified assumptions of 100%: conversion of **EB** to **S** in the dehydrogenation side; transport of produced H_2 from the dehydrogenation to the hydrogenation side and transport of heat from the hydrogenation side to the dehydrogenation side. More accurate distributed results can be obtained by using a **MM** for this Membrane Integrated Reactor.

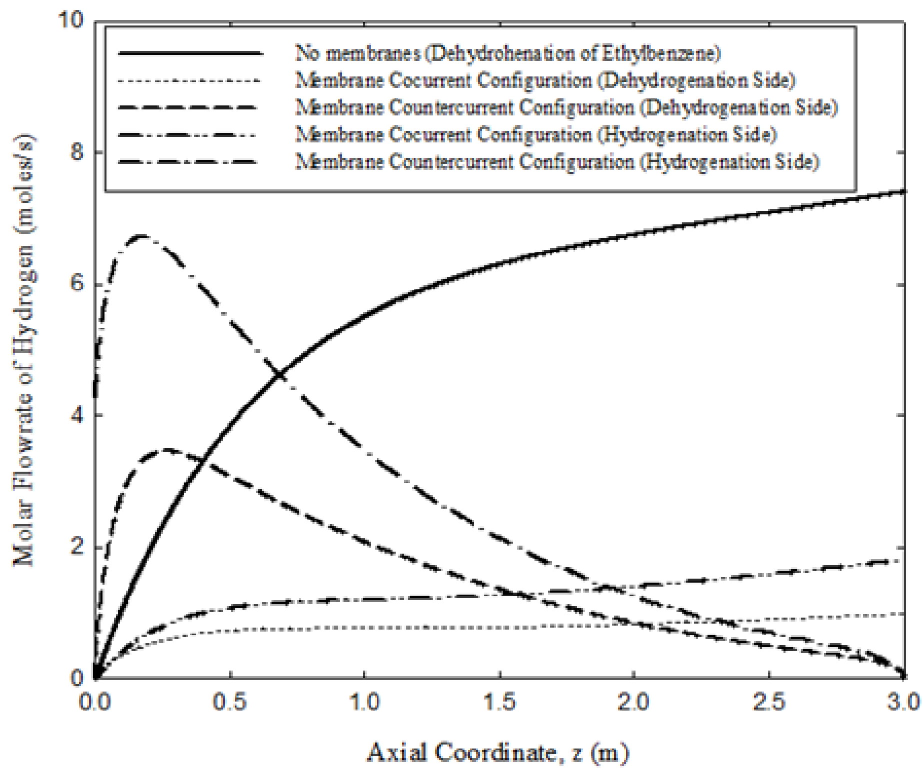

Fig. 6: Hydrogen profiles for different configurations/sides.

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