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Article

Design is how we change the world! Can we do it in socially, environmentally and economically acceptable ways? Synthesizing design tools for this utopian concept

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Abstract: Since the beginning, humans advanced their civilization by making better tools to improve their lives. Tools and products were designed for better living considering manufacturing issues, cost and time as predominant criteria. It has become clear that not considering environment and society, both at local/global levels, has now become a major impediment affecting living conditions on a large portion of the Earth and in many societies. Design methodologies should lead to creative solutions with consideration to engineering and economics for practicality but also to environmental and social constraints for sustainability. We propose a comprehensive design methodology based on multidisciplinary design to include the knowledge of humanities, environmentalists, science and engineering, and allowing for experts' inputs from these areas to provide a holistic approach to engineering design. For example, experts in humanities are expected to interact with stakeholders to evaluate their value systems to provide guidance for the design. The methodology that we synthesize is new and combines (i) Societal level impacts at all scales, (ii) Environmental impacts and (iii) Engineering design with economic impacts, including uncertainty considerations. The proposed design methodology is called Social-Environmental-Economical-Engineering Framework (SEEEF). It can utilize concepts and tools such as Circular Design, Doughnut Economics, design based on environmental life cycle analysis, among others. SEEEF is quantity based and provides steps for evaluating any project or product in an objective manner and will help train engineers in design for sustainability. It also provides non-engineers with a significant role in design to increase their understanding of the hard constraints of engineering. Ultimately, SEEEF allows society to take an informed decision considering short/long term and local/global impacts of the design and the pertinent uncertainties.

Keywords: design for society, design for sustainability, design under uncertainty, circular design, donut economics, life cycle analysis

1. Introduction

Economics and Engineering based designs go hand in hand especially since the industrial revolution. Industrial production meant that a societal demand was expected for the product and thus some aspects of the society were considered. Local environmental issues were most likely considered either for practicality (earlier days) or by societal regulations (later days). Until recently, global impacts were rarely considered and the ability to account for various temporal and spatial

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impacts are still in development [1]. However, we now know that almost all products have both local and global impacts on the environment and society, even when small at a given time/space coordinate the cumulative impacts will be significant over some length of time. Considering product design with respect to engineering, economics, environmental and social constraints may appear daunting (here, unless we say specifically, local and global, and short and long term impacts are always considered in the design process). At these scales, uncertainty is a major component and is included in the design process. However, sufficient understanding of how one might consider these constraints individually in a design, even under uncertainty, are available but no design framework exists which could combine all these objectives jointly. One may wonder that, even if we had such a design framework, given the national divisions and different political philosophies, would it be practical?

We propose a design methodology named as the Social-Environmental-Economical-Engineering Framework (SEEEF), see Figure 1. Existing methods include: circular design [2], product design using large amount of data now available [3], (environmental) life cycle design [4], bioinspired sustainable product design [5] and sustainable design could that could induce change in consumer behaviour [6]; In addition, trade and bi-lateral and international agreements control most products. Our aim in this paper is to use all these existing ideas to develop a framework that is implementable at various levels considering both local and global constraints. Recently, Amsterdam city has agreed to a progressive design procedure called Doughnut Economics [7-8], which considers the same issues we will tackle. The difference is that we provide synthesis of existing design methods with new metrics required to consider local/global and short/long term impacts. The method can be applied in practice to achieve what is analyzed in [8]. It is also noted that both Environmental and Engineering modules depend on both fundamental and applied science and hence there is no separate module for science. In other words, each of these modules have been used alone as a decision tool in the past but SEEEF provides a method for combining all four viewpoints at the levels required to be of use in practice.

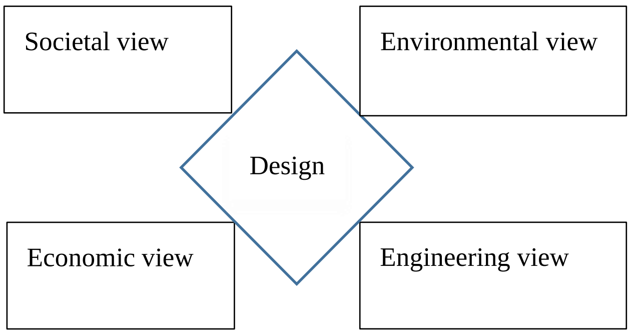

Figure 1: SEEEF Diagram

Motivational example: Recently Joe Biden, a candidate for presidency in the USA announced a $2 Trillion investment to bring on more renewable energy in the country [9]; this is a major design project affected by all four views considered in SEEEF and we will use this as an example (named REPUSA) to demonstrate the design process and various individual methods. There are conflicting opinions on this energy project including the biggest problem being of societal acceptance. It is not hard to imagine the not-in-my-backyard (NIMBY) phenomenon as one of the societal problem, in addition to problems such as uncertainty in demand and supply, land costs, environmental issues, trade and other policy issues, any design must meet economic and engineering constraints. In today's societal situation, where a large number of people are unemployed, even if cost of materials for this product and imported labour to install it is much cheaper from other countries under a trade agreement, the solution of simply importing may be unacceptable for a large part of the local population. Our aim in this paper is to provide details of SEEEF synthesizing various design methodologies considering not only engineering and economics views, but also environment and

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society with necessary adjustments. We provide a method for holistic design considering all these four views considered from the beginning of the design or redesign. A project may include just a single product and such a situation is more common to an individual company (iPhone of Apple is a good example) or many "products" which is likely the mandate of governmental level organizations (REPUSA). *SEEEF* includes methods for designing products and projects. It can utilize Doughnut Economics that is primarily an evaluation tool and more comprehensive than Circular Design that is product specific and does not include societal influences.

2. Designing at a societal level: feedbacks and scale challenges

Designing at a societal level means that one has to consider impacts on humans at local, regional, national and global levels as well as considering both short and long terms objectives due to intergenerational challenges. On the other hand, it is obvious that considering societal impacts cannot be comprehensive without interacting with other views and SEEEF will address this issue.

SEEEF considers the system as a whole and society is an example of a system to be studied in the society view module. Identifying all components of a system is a challenging activity but has been made easier today with large amount of knowledge and data available even in electronically readable forms (similar to what is made necessary for environmental life cycle analysis LCA [10] by one of the early proponent–the society for environmental toxicology and chemistry commonly known as SETAC). Each individual and interacting component of a system, whether it is civil, electrical, mechanical, computational, biological, societal, among others, can simply be represented by its functionality and its interface. While the detailed design of individual components may be the responsibility of the respected field of specialty, integrating these diverse components such that they work together effectively as a whole is our system design objective.

Design is a creative problem solving exercise; identifying stakeholders, their objectives, their criteria and corresponding measures form the very first steps. When designing for a society, the objectives could be separated by short and long term, and local and global and feedback between these differing scales. For example, in REPUSA project, a short-term objective could be to meet current local demand as a certain percentage of the total local demand (for simplicity we will consider just photovoltaic solar energy here). However, for long term, this percentage can be set to a higher value (the optimal value itself will be a result of the application of SEEEF). In addition to this objective, REPUSA may be forced by international agreements to have a stepwise long term plan for the entire USA, thus changing local installment capacities as part of a long term strategy. It is also noted that an international agreement on say, greenhouse gases (GHG) limitations, specific for the USA can be converted to an equivalent renewable energy target (assuming all targets are met solely by the energy sector which, of course, is a simplification for explanation purposes and could be extended to sector by sector targets). However, at the societal level, meeting energy targets by renewable energy is just one objective that can be measured in kilowatt per hour of the energy actually provided. On the other hand, this environmental objective on energy, even if it is achieved, may be completely unacceptable if we do not consider other societal goals such as maintaining an employment ratio or sufficient income for local conditions (as it may be necessary to reduce employment existing from other sources of energy locally produced). It should not also be degrading aesthetics as other environment related societal constraints (for example, how much local and global toxicity may be allowed and for how long and what current and future remedial solutions have been identified; all can be dictated by the society to the environment view module). Nor should it be degrading land use for other purposes like farming and forestry. It must create no adverse health impacts, and equitable share of land resources for energy generation (for example, the province of Ontario in Canada, during the McGuinty government, received public input regarding the extension of what is called the Microfit program that supported increased solar energy installations; the first author suggested, possibly among others, a model where local body of people should have significant share of the renewable energy development and this scheme became a bigger success and with much less NIMBY problem and increased significantly renewable energy installations in Ontario). Unless an objective such as

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equality or equity and the affected stakeholders has been identified, it is not possible to find a solution that requires policy changes at various governing levels.

In summary, the societal view module of SEEEF will accept inputs such as plans and policies and return merit scores for various objectives affecting all stakeholders. Societal module inputs include the society's objectives (targets time series, allowing for progressive changes in income, equality index, environmental values, and others). Even aesthetics objectives can be specified (for example, with stakeholder meetings targets of non-aesthetic parts of solutions can be restricted such as requiring no more than 10% of the area for solar panel layout, etc) as well as possible plans and solutions. SEEEF will pass on these plans/policies/targets to other modules to get appropriate scores and sensitivity of these scores for chosen decisions and constraints. The scores will have short term and long term results corresponding to various local regions identified and global sum of all local regions and beyond. Scores will be presented with at least means and (co)variances for each criterion so that uncertainty is explicitly stated. It is also possible to include fuzzy logic analysis to consider uncertainties which are not captured in a statistical sense. A decision screening analysis can be done using a multi-objective and multi-criteria analysis when stakeholders are consulted again in groups with explanations of score impacts on their group; even the same objective can produce multi-criteria results (for example, REUSA demand satisfaction according to a constraint can produce employment results in income as well as equality levels such as the Gini index that measures equality). A chosen selection procedure can then be applied for choosing the final decision (many methods exist such as AHP [11], conjoint analysis of choice [12], and so on, and are not provided in details here). In the Engineering module, described later, detailed parts of designs are addressed which, of course, are not needed at the higher level of decision making. The decision module where final decision is made using above-mentioned tools is also a communication module passing the required inputs to other modules and collecting the outputs or feedback from those modules to make the final design.

3. Design guided by environmental life cycle analysis

Environmental life cycle analysis (ECLA) is a different method from the life cycle analysis considered in economics that is mainly concerned with useful machine life; ECLA can be used to design products considering their impacts from cradle-to-cradle. Products go through many transformative processes, namely, mining raw materials from natural sources (from earth which is the cradle) to condensation process to manufacturing and transportation to consumptive use and eventually disposal back to nature (cradle again). Moreover, at each of the intermediate steps, effluents of the processes also go to nature and may require other resources such as land, water, air, and energy. The impacts of any product on the environment are measureable (whose accuracy is continuously improving since the 1990s) in terms of environmental target variables; for example, land area used, GHG emissions, toxicity to water and land, among others, and can be made available using software such OpenLCA [13]. Any proposed design is evaluated in terms of environmental quality indices for the given design coming from the engineering module.

For the example of REPUSA, the constraints on land, GHG emissions and aquatic toxicity are some of the key environmental target variables. This could vary both locally and globally and can be different for various time periods. Taking the example of some rare metals used in photovoltaic systems, the target for next few years (the length of time itself can be a design variable) can be different. It is possible that with given targets, more incentives exist either to design such that it can be recyclable or replace some of the rare metals which are highly toxic over a longer period of time. Both Circular Product design [2] and sustainability based product design [4] consider these issues in detail. A difference between these and the proposed Environmental module in SEEEF is that we will include uncertainty in our design so that the output scores on various environmental variables reflect both means and (co)variances of impacts. This information is used to take final decisions whose risk factor will be jointly measurable with the expected scores. Also, another major difference is that the scores are expected as a function of time and location. For example, source pollution is given separately from transportation pollution; if main transport is through ocean, then it is separately provided compared to pollution from land transport and pollution during consumption/disposal. This level of detail is necessary to bring more equity as pollution in a city has more impacts than on an unpopulated area. However, in a global sense, cumulative impacts will be considered as pollution anywhere can result in problem everywhere; for example, the GHG emissions!

4. Design under uncertainty in cost, manufacturing and engineering

This section covers the well-known highly interlaced Economic and Engineering modules. Since we would like to understand both local and global issues, we also discuss trade issues as trading makes it more efficient in an economic sense. The content in these two modules have been in development for a long time and hence we provide only the minimum needed to understand SEEEF. Most of the development in civilization came from one major economic concept called the economy of scale which, in simple sense, translates to lower costs of products when produced in large quantities and hence increasing their reachability to many people. This concept cannot be implemented without applying engineering principles. For example, ancient humans figured out how to make mud pots (which made cooking food possible with water, leading to a huge improvement in living conditions). In the beginning, only artisans were able to make these pots. However, as soon as wheel was invented (an important engineering invention), artisans not only could make many pots in the same time, they were able to train others to create even a larger number of pots. A craft work migrated to be an engineering work. A similar pattern followed also in software that went from codes crafted by a few to APIs that many can use, producing numerous number of Apps at hugely reduced cost. Hence, the drop in the cost of a pot or software increased the possibility of more people acquiring it. The concept of economy of scale tied economics with engineering. The reason that so many products are being manufactured in China today is because of the economy of scale. This is made possible due to the availability of a large number of cheap-skilled labour working extremely large manufacturing facilities. A big advantage that is unmatched by any other country today. The USA was in a similar situation after the second world war and it still has cheap farm labour and relatively inexpensive software engineers, both due to a large number of people who arrived from other countries. Between these two countries, this has led to the balance of trade favorable to China in consumer products manufactured in factories and favorable to the USA for technological products and services that depend on a large number of skilled workers (software engineers being a major group) in the service industries.

The same economy of scale that made it possible for numerous number of products being affordable to a large population also produced a large side effect, which is the pollution from the waste materials. People could acquire a large number of products as they were available at a much cheaper price but a lot of them were not "necessary" ending up as being unused or thrown as a waste. Therefore, this major side effect is an important reason why we need the Environmental module in SEEEF. These pollution penalties were originally considered by economists as "external", as the pollution generally affected neither the producers nor the consumers (in the first glance). In order to make the polluter pay, laws had to be formulated (to be considered in the societal module), to discourage "unnecessary" buying and to discourage producing "non-recyclable" products. Local costs are simply fees such as deposit fees but costs from global impacts are to be taken care of by international agreements leading to costs such as the carbon tax. Therefore, the Economic module will be used to make decisions on costs (both of the local kind and of the global kind) and will be used in the Engineering module. It is noted that import tariffs are nationalistic way of making locally produced products more attractive (leading to potential increase in local employment) and this must be traded off with other side effects such as local pollution and reduced consumption from higher costs on products, which is not necessarily bad for the environment.

A major input to engineering module are short term and long term demands and the cost evaluated at the Economic module as well as their uncertainties. Uncertainties are considered in the first two moments estimated in the Economic module. However, those uncertainties themselves

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could be affected by solutions that are provided by the Engineering module. Hence, these two modules are tightly interlaced and could be considered as a single module.

Typically, the Engineering module is used to find implementable solutions for given costs and engineering constraints. There are two types of engineering design problems; one in which the design variables are uncertain (due to tolerances in manufacturing processes) and the other where a design can be determined with certainty but consequences of the design during the (environmental) life cycle of the product are uncertain which could include both cost uncertainties and variations in production technology. In addition, the Economic module may provide demands and their associated uncertainties and hence the Engineering module has to take these factors into account before a solution can be found. The output of the Engineering module is both mean values and (co)variances of costs; it is also possible that these may relate to multiple objectives; so costs does not mean only money units. It could be other measures like time, pollution level, etc.

The REPUSA problem can be used for explaining some of the issues such as the design variables uncertainties versus design under uncertainty in consequences. Photovoltaic (PV) wafers are manufactured in large quantities in integrated manufacturing. Depending upon the material and processes used, the performance (due to components in the wafer) of PV cells are uncertain. For now, let us just consider the light to energy conversion efficiency that is the main reason for using PV cells. Therefore, the total energy produced even under constant light input may vary. The better the processes and materials used, the less the variability in energy produced but higher the manufacturing cost. Therefore, one of the design problem here is the amount of material/process variability that could be allowed. This is one kind of design problems where design variables are uncertain [14]

The second kind of design problems is how many of these PV cells to install (how many panels in reality) given the energy demand and the uncertainty in energy demand. In addition, there is also input uncertainty (that is the amount of usable light available to convert to energy) and given all these uncertainties, each decision we make to install the energy production capacity (consequence) is uncertain [15]. Such a decision cannot be changed in short to medium terms. Engineering module is typically coordinating with the Economic module to come up with various decisions and their consequences.

Because manufacturing includes materials and processes, it also produces output that are of interest to the Environmental module. For example, should we remove CO_2 locally [16] or just send it out to the atmosphere with a chimney. We already saw that engineering/economics solution also involves national and international issues such as employment versus cheap product cost interacting with the society module. Therefore, we need a holistic framework such as SEEEF to be able to elicit various solutions and their impacts on all of society and environment in order to make a sustainable decision. The decision itself now depends on value systems elicited by the Societal module interacting with all stakeholders.

5. Social-Environmental-Economical-Engineering Framework (SEEEF)

Design for society and sustainable design has been studied at least since the early 1990s [17-20] and new organizations have been started by various private, public groups and governmental organizations. The awareness and working towards sustainability is at high level but tools for practical implementations is lacking. A common mistake of many of these works is to ignore the engineers while the other more common weakness of engineers has been not getting enough training and inputs in society and environment [21]. After all, at the end, most implementations require engineering and, if engineers have not been part of this movement and have been trained to think in the same holistic way, there is little chance for real change. One of the earliest institution to encourage engineers to think holistically is [22] and even that program requires much change as sustainability is not the central theme of the program. A common fear of asking for sustainability in design is that it is not practical for use today. What is lacking in our designs and policies is that while engineers provide the society's requirements for a project or product with the knowledge and skills available at that time, there is no systematic analysis of what parts of their solutions should only be used for limited time requiring changes or replacements for an improved sustainability. An example is the replacement of CFCs from cooling appliances, although the science connecting CFC to ozone hole came late and a knowledge that was unavailable during the design period. Hence, the need for continuous assessment and encouragement of independent and fundamental scientific research becomes apparent. On the other hand, the use of microbeads in consumer products could have been easily prevented from being used at design stage if some care has been taken to train designers in sustainability and design for sustainability had been encouraged. The major theme of SEEEF is that any product considered in design will have a list of issues regarding their suitability to meet societal/environmental constraints identified and change plans made over a specified length of time to meet these constraints. We have started doing these in patch works of problems. For example, when new pipes are laid in water system, most regulations today require us to have no lead in new pipes as lead has been found to be harmful to people and environment. Reducing and realigning roads to encourage less motor vehicles and reduce speeding, and more bicycling, etc., is another example. On the other hand, SEEEF can be used now to redesign existing products as well as new design of products and projects.

6. Final Remarks

Since the 1990s designing for society and environment has been promoted and many tools that can be applied with focus on some specific issues have come to life. Some of them like Doughnut Economics is comprehensive but are not specifically design tools and some like environmental life cycle based designs are good but not comprehensive. More specifically, they do not consider serious social issues like employment and trade. SEEEF is promoted here to overcome these shortcomings and provide a true interdisciplinary framework where specialists from humanities, and engineering/science take appropriate roles. SEEEF forces communications with stakeholders and among all specialists as an essential part of the decision making process to achieve either product redesigns or new designs of products and projects.

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