Engineering Sustainability – What's New?

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Abstract. In recent years sustainable systems are recognized as an important goal to be achieved and vital in a circular economy. Hence this subject is also gaining more attention on SE conferences. But what's new? The Systems Engineering process already emphasizes systems thinking and life cycle approach, fundamental concepts for optimizing sustainability. This paper argues that on one hand (SE wise) there is nothing new with sustainability, but on the other hand there is a general lack of knowledge among systems engineers about methods to optimize sustainability in the design of systems. This paper will give an overview of these methods and areas for development for the systems engineering community.

Introduction

In 2015 the United Nations issued the "2030 Agenda for sustainable development" Ref.[1] including 17 sustainable development goals which are presented in the following poster: see Figure 1.

Figure 1. UN Sustainability Goals 2030

This document presents a vision for a world free of poverty and hunger, with respect for human rights, safe drinking water and sanitation, and access to affordable, reliable and sustainable energy. A world in which consumption and production patterns and use of all natural resources are sustainable, and where development and the application of technology are climate-sensitive, respect biodiversity and are resilient.

Many of these goals are of interest for the Systems Engineering community, especially the goals “Affordable and clean energy”, “Sustainable cities and communities”, “Responsible consumption and production” and “Climate action”. The key enablers for these goals are sustainable systems, for instance “sustainable transport Ref.[3]. This report recognizes that realizing sustainable systems requires a holistic approach, involving many stakeholders: “*The transport sector is large, diverse and complex, and infrastructure decisions and investments have an especially long lifespan*” it says. As Systems Engineering claims to have the methods and tools for addressing the problems in development of complex systems, see INCOSE Systems Engineering Handbook, section 2.8, Ref.[4], the systems engineering community should play an active role in the development of sustainable systems.

In this paper we will give an overview of current trends in sustainability engineering, and provide some insight in how sustainability can be integrated in the Systems Engineering process, and also mention the methods which can help to implement this.

Definition of sustainability

The term sustainable is quite often used in the meaning of a system ‘that can be continued to be operated, or maintains itself’: a rather technical meaning. In recent years this meaning has been widened to: ‘that can be continued to be operated without harm to the environment’. The Brundtland Commission of the United Nations has defined sustainable development already in 1987: ‘Sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs.’ So this meaning of sustainability is extended to sustainability of the whole earth system (that can continuous operate and maintain itself – also in the future). This has implications: sustainable systems must not only protect and enhance the world’s natural systems and resources, but also enhance social systems and human well-being.

Presently applied systems engineering in relation to sustainability

Sustainability in the Systems Engineering community

The terms “Sustainability” and “sustainable” can be found in the INCOSE SE Handbook, Ref.[4], but just in a few places, mostly in the meaning of a system to “continue to be maintained (operated) at a certain level”. In chapter 10.3 the area of Environmental Engineering is presented as a “specialty engineering” discipline. However, the emphasis of this chapter lies on the environmental regulations and the compliance with those regulations. Chapter 3.3.6 describes the ‘retirement’ life cycle stage, but only mentions that disposal requirements must be satisfied. Hence the subject of sustainability, as described in the paragraphs above, is not getting detailed attention in the INCOSE SE Handbook. At the INCOSE Conferences however sustainability gets increasing attention through the years. The INCOSE Vision for 2025 Ref.[9] also recognizes sustainability as one of the systems engineering challenges. It presents eight key system characteristics desired by stakeholders: sustainable, scalable, safe, smart, stable, simple, secure and socially acceptable. The vision states that “*Systems engineering will also contribute to assessments and analysis of socio-physical systems such as the global climate system to inform stakeholders and decision makers of the emergent impacts of organizational and public policy actions*”. The vision addresses also a number of specific areas where Systems Engineering can contribute such as the development of Systems of Systems, the Internet of Things, multi-variable optimization and integration, managing many stakeholders, and so on. But the question “how” this can be done remains to be answered.

Systems approaches as applied in sustainable development

A systems approach is widely recognized as necessary for sustainable development. An example is The Pennsylvania State University which has an online course “Technologies for Sustainability Systems” that explains systems approach as the primary framework for applying sustainability principles, Ref.[8]. Systems thinking is applied to explore the relationships between technical and eco-systems, and Life Cycle Analysis (LCA) is used to assess and compare the life cycle long impact of products on the environment.

Several frameworks have been developed for sustainable development. A few of them:

- The Three Pillars for sustainability, also known as the triple bottom line (TBL), or 3P: People, Planet, Profit. This shows that social and environmental concerns are also important for businesses, and not only profits and losses. Ref. [34].

- The Five Capitals: Natural, Human, Social, Manufactured and Financial capital. This provides a basis for understanding sustainability in terms of the economic concept of wealth creation or ‘capital’. If nature, humans and social value are considered a capital, like financial capital, any organization would try to prevent loss or waste this capital. Ref.[10].

- Cradle-to-cradle, Ref.[11]. This concept introduced the idea that, just like in biological cycles waste becomes food, also industrial cycles for products and materials should exist where there is no waste anymore. So rest products and materials become food for new products (upcycling):

  Waste = Food

- The 12 ‘Guiding Principles’ of Engineering for Sustainable Development, Ref [12]. This document also provides advice on the application of the Guiding Principles in practice by relating them to five main stages in any engineering project or enterprise.

- The 12 principles of green engineering according to Anastas and Zimmerman, Ref [13].
- The Sandestin Conference Declaration in 2004 which defines the 9 Principles of Green Engineering, Ref.[14].

The first mentioned Three Pillars Framework can often be found in literature as three interacting circles, and is also used in the INCOSE Vision 2025 (Ref.[9]) in Fig. 2.

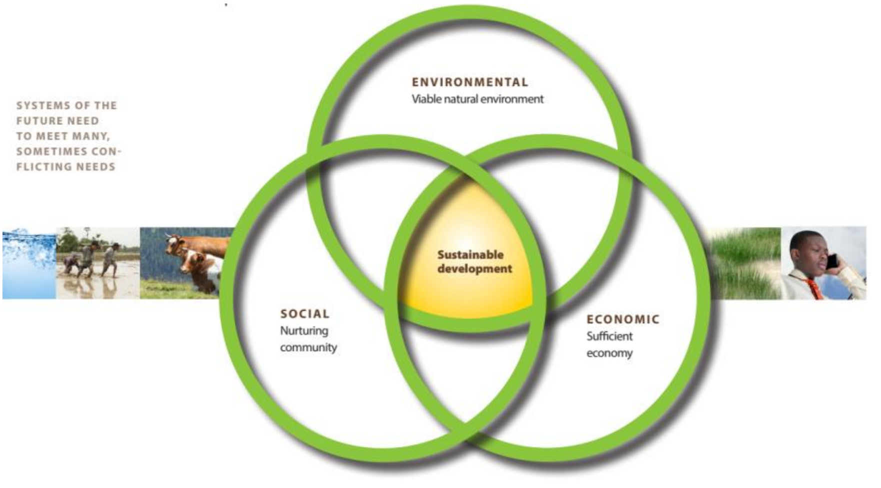

Figure 2. The Three Pillars for sustainability as illustrated by INCOSE (taken form Ref.[9]).

The frameworks described above mainly provide general guidelines for sustainable development. The following Systems Engineering concepts can be found in these frameworks: holistic thinking, life cycle thinking, integration, stakeholder engagement, explicit needs and wants, effective planning and management, seeking balanced solutions. Also guidelines are given ranging from technical design guidelines to political guidelines, in a rather random order. In the literature on sustainability many other concepts are presented for instance the circular economy, design for disassembly, environmental reporting, life cycle analysis, renewable energy systems and so on.

In the following chapters a general overview is given of the various concepts and methods related to sustainability, structured in such a way that it may help to get insight in the relations and dependencies between these concepts. Furthermore this paper gives some viewpoints on their consequences for Systems Engineering.

Sustainability Engineering concepts and methods

Introduction

We have seen in the previous sections that sustainability can cover anything from simple products to socio-economic systems, from product life cycles to complete supply chains. In order to get a systematic overview of the sustainability concepts we will structure the information in this paper along the 5-layers systems engineering model of Prof. D. Hitchins, Ref.[15], [16], and [32]. The five system layers according to Hitchins are:

- Level 1 - Product level. This is the basic level of tangible artifacts: products that perform basic functions.
- Level 2 - Project or System level. A system is made of several products that interact with each other to perform some or more integrated functions. Most Systems Engineering projects work at this level to realize systems.
- Level 3 - Business Systems level – a business consists of several projects and can develop or operate systems to produce services.
- Level 4 - Industrial level, or complete supply chains/circles. An industry is made of several businesses.
- Layer 5 - Socio-Economic level. Many industries make a socio-economic system. This is also the level of the social system, regulation and government control.

This is illustrated in Figure 3 which will be explained further in the next paragraphs.

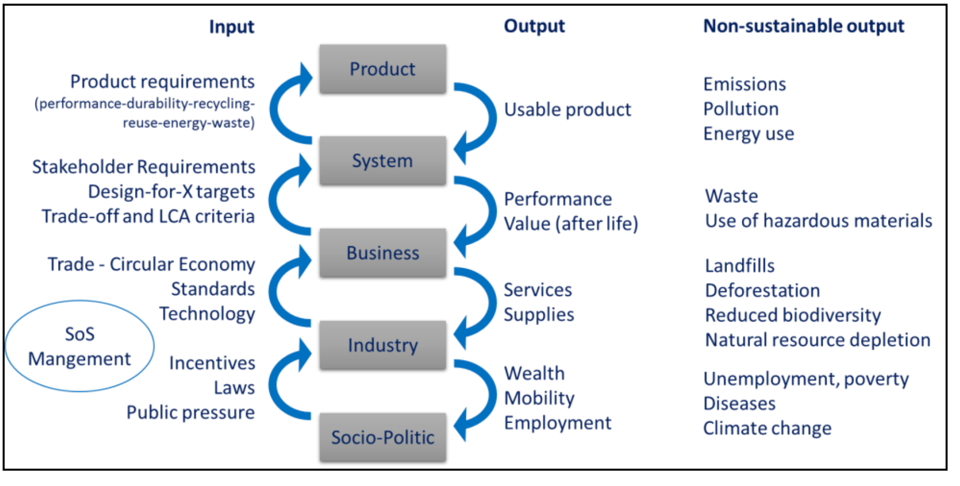

Figure 3. Sustainability in the Hitchins five system layers.

Note that the big overall system is level five at the bottom and products are on top as level one. One would expect a hierarchy with the big system on top and products at the bottom. However it is sometimes presented by Hitchins this way, and for this paper it is done also because it helps in understanding the dependencies. The system life cycle processes (Ref. [6], [32]) can be applied to any of the 5 systems layers (even socio-politic systems have life cycles).

Level 1 – Product level

On the product level sustainability can be achieved in a rather straightforward way: tangible products (or simple systems) have a clear function and transform an input into an output. Inputs consist of materials and energy. The sustainability design targets include minimize input materials and energy, avoid hazardous materials, and use renewable energy and recycled materials. Outputs consist of the primary result (function) and non-wanted outputs such as waste and emissions which can be hazardous for humans and the ecosystem. The sustainability design targets are minimization of waste and emissions for a given performance.

The product itself transforms input into output, and has a certain efficiency and durability (lifespan) doing so. Sustainability design targets are maximizing efficiency (thereby minimizing inputs) and good targets for durability and capacity which are fit for purpose. Built-in overcapacity and over-durability may have a negative effect on sustainability because it results in more than necessary materials, energy use, waste and emissions (although this overcapacity may well result from economic considerations for standardization).

Sustainability at this product level is mainly concerned with reducing the negative impact on the environment, and Eco Design was one of the first methods for sustainability engineering. But there is more: products have a life cycle, so that raised questions like: what is the environmental effect of a production line? What happens when a products life has ended?

The product Life Cycle

Products must be developed, produced, tested, maintained and disposed of. This life cycle also uses resources and energy, and causes waste and emissions in addition to those related to the primary function of the product. Life Cycle thinking takes this into account.

The product life cycle is a fundamental concept in systems engineering, but is always presented as a linear line from concept design on to disposal. The term disposal suggests that a product becomes waste. But instead, a sustainable system after dismantling does not create waste anymore, but its substitutes can be used as input for the creation of a new system, and hence represent a certain value: Waste equals Food (Ref.[11]). Linear thinking becomes circular thinking. That is why a circular oriented life cycle is a better model regarding sustainability, as already mentioned in Ref.[5]. See Fig. 4.

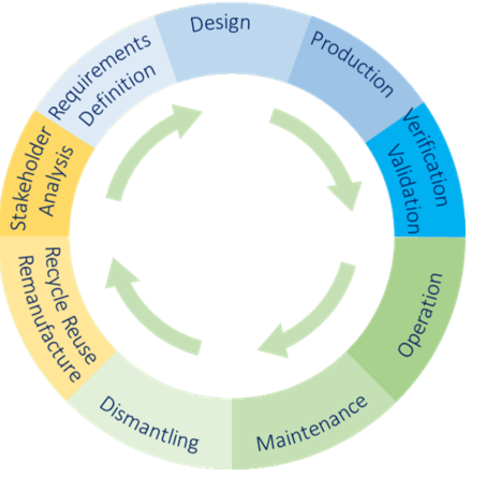

Figure 4. A Circular Life Cycle

Consequences for Systems Engineering at product level

A number of consequences for Systems Engineering evolve from the above discussion:

- The life cycle needs to be defined more precisely. Several life cycles are to be considered: that of the system of interest, and that of its products and materials. A reused or remanufactured part has a longer life cycle than the system it was a part of. There are generations of system life cycles: the output or end-value of a disposed system provides new input for a next generation of systems. Examples are midlife upgrades of trains and airplanes and the development of system families such as the Boeing 737 aircraft family, where parts and subsystems can be reused across the family members, along with introduction of new items.

- Not only the product itself, but also the information regarding the product becomes relevant for new life cycles: so Information and Configuration Management needs to be applied beyond the systems life cycle.

- Stakeholder requirement definition gets involved with new stakeholders: A balanced planet becomes a new system requirement, Ref [23]. Sustainability requirements may originate from many sources: the customers, the developing company which sets sustainability goals for its own products and its supply chains, the recycling industry, and legislation and politics in the form of industry wide guidelines and rulemaking. The requirements originated from these stakeholders must be measurable requirements. That will require target levels for the several sustainability parameters, targets which are feasible to realize on one hand and ambitious enough to make progression.

Where do the product requirements come from? They can only be defined at the next level, the systems level: product requirements are the result of a balancing effort of environmental and economic effects over the whole system and its life cycle – including its production system, maintenance system, operations systems, and disposal system. So here we have arrived at the next level: systems.

Level 2 – Project or systems level

This is the level of primary systems (who fulfill the needs) and their “enabling systems” which facilitate the life cycle (development, operation, maintenance and disposal) of the primary systems. Sustainability analysis at systems level means an integrated process of careful allocation and balancing of sustainability requirements and budgets over its sub-systems/products and the enabling systems.

Design-for techniques

To facilitate integrated and sustainable development over the systems life cycles the so-called Design-for-X techniques can be applied. Numerous techniques and guidelines are available. A good collection of references can be found in Ref. [8] and [22]. The following product Design-for-X concepts are relevant for the design of sustainable products:

- Design for Reuse: defining architectures which allow reuse of sub-systems or parts, by extending the life time (Design for Durability)
- Design for Remanufacturing: defining architectures (and processes) for the possibility of restoring a component or a system to a new state and sell it again
- Design for Recyclability: apply recyclable materials or degradable materials (such as bio based plastics, biodegradable plastics) and define the architecture in such a way that these materials can be easily separated from others.
- Design for Disassembly (in contrast to the established techniques of Design for Assembly for new products), necessary for separating parts and materials for recycling.
- Design for Adaptibility: defining architectures and solutions that can be easily modified to adapt the system to new requirements or interfaces.
- Existing design-for-X techniques such as Design for Maintainability, Repairability, Upgradability, Compatibility, are very helpful in this regard.

Some examples: Smartphones are difficult to recycle because in general they are not made for good disassembly. Kodak produces one-time single use camera’s - that looks not very sustainable, but they developed a way to take-in these camera’s when used and to resell them after refurbishing as new. In modern aircraft many parts and equipment can be reused in other aircraft. But there is also a problem that the optimization for aircraft economy and performance (minimum weight) has led to development of strong and light weight composites materials that are difficult to separate and recycle.

Enabling systems development

Sustainability is not only related to the system of interest, but has also implications for its enabling systems. You can design a public transport system based on electric driven busses, but this means that the whole infrastructure for energy delivery (which is an enabling system for the bus operation) needs to be transformed from fossil fuel to the delivery of electricity and charging batteries. And this electricity should be produced sustainably, otherwise there is no environmental gain in total.

Production systems contain many challenges regarding sustainability in areas such as toxic materials, painting and conservation techniques and logistics. Logistics include normally globally distributed making and transport of parts and components to an assembly line, and redistribution to customers. This transport itself can be regarded a form of waste (useless energy) because it adds no value to the product use. This waste should be explicitly traded against the lower costs and social aspects of production in low-labor cost countries (where such production could even have a positive effect if managed properly). The reuse, remanufacture and recycling of products will introduce also new enabling systems and logistics, leading to interesting trade-offs: more recycling (more sustainable) means more energy use and more transport (less sustainable).

Life Cycle Analysis methods

Life Cycle analysis is used as a tool to calculate and balance the environmental impact of a system over its complete life cycle including the impact of its enabling systems. There are already numerous life cycle calculation methods and tools available for these purposes. The sustainability engineering discipline must know how to apply these methods and tools. Life Cycle analysis methods calculate parameters such as for instance: materials consumption, energy consumption, the use of hazardous materials, the use of water, land use, system emissions such as greenhouse gases, and waste. Life Cycle assessment methods are standardized through the ISO14000 series standards, Ref.[18]. For each of these parameter “footprints” can be calculated.

A new concept is an extension of traditional LCA methods and is called: Life Cycle Sustainability Assessment (LCSA), Ref.[19], [20], [21]. It integrates LCA with social Life Cycle Analysis (sLCA) and Life Cycle Cost Analysis (LCC), that account for the social and economic domains of the system:

$$LCSA = LCA + sLCA + LCC$$

Life Cycle Sustainability Analysis provides the designer with many parameters to be used as design trade-off parameters, meaning one can optimize the design in numerous ways. People performed assessments using up to 40 parameters! The trade-off process becomes multi-dimensional and establishing the trade-off criteria is an important step in the design process.

Essential for a proper LCA comparing different products or variants is the system boundary definition especially regarding the extent of the impact of enabling systems.

Consequences for Systems Engineering at project/systems level

A number of consequences for Systems Engineering at this level are:

- Sustainable products may require continuous engineering & development during the operational phase, and even beyond the product life cycle (of the SOI), see Ref. [17]. This is because there is rapid evolution of clean technology, regulations and supply chains because of new recycling and reuse patterns. This has consequences for the life cycle phases as used in systems engineering. An OEM is required to engineer updates to its products. Traditional systems engineering with a set of pre-defined goals and requirements is now faced with rapidly changing requirements. Design for adaptability.

- Systems Architecting: the sustainability concepts of reuse, remanufacturing, disassembly and recycling need to be integrated in the architecting and design process. If components are to be standardized for use or reuse in more than one application, these components must be validated for use in different environments, requiring a reference architecture and component models which defining scope, requirements and interfaces for these components.

- Design & Trade-off: LCA techniques can provide even too many parameters for the design trade-offs. These parameters cannot be easily scored or traded against each other because they have different units. Possible approaches are prioritizing parameters Ref.[24], multi-criteria trade-off techniques, and monetizing sustainability costs or value. Calculation of the value of nature, biodiversity, world temperature rise, and social well-being is difficult, in spite of much research already carried out. Also these parameters need to be integrated in the design tools in some way.

- Verification: New legislation is developing in the area of assessments or certifications for environmental impact. Sustainability reporting and certification takes place at product/systems level but also at business level. Examples are: Life Cycle Analysis, the ISO14000 series of standards, and the ECD, the Environmental Product Declaration which is encouraged in the EU but not yet mandatory. For instance Bombardier issues EPD’s for its trains and aircraft, Ref.[7]. EPD’s scores the product on parameters like Energy use, Material use, kg CO2 equivalent, and acidification. There is also existing regulation of EU directives on subjects like hazardous materials, energy labeling of products, and Green Public Procurement criteria.

- Recycling Plan: The best way to incorporate design-for techniques, LCA methods, and integrate enabling systems in Systems Engineering is: make a recycling (and reuse, and remanufacturing) plan during the product design phase, and involve the recycling industry in the design. This plan should define the trade-offs to be made to balance the sustainability of the life cycle systems and minimize the total life cycle impact.

But where do the criteria for design-for-X and trade-offs come from? Who defines the optimum balances between reuse, remanufacture, and life extension? Who defines the allowable costs and risks concerned with achieving sustainability? That is to be done at the business level.

Level 3 – Business level

The business provides services to customers and to other businesses, for which it operates systems. These systems provide value, performance and income, and cost money and risk. So business engineering is concerned with balancing these costs and incomes. Therefore the business must define the performance requirements, cost- and risk targets, the trade-off criteria, and opportunities for recycling, reuse, remanufacture. The business model can stimulate sustainability but can also have a negative effect. Traditional business models based on maximizing production and short term profits have proven to be non-sustainable. This linear (in stead of circular) thinking has led to built-in aging and bad repairability to stimulate selling new products. As stated in Ref. [33]: *"Most designers are not aware of the fact that everything they do is defined by an implicit business model, and that this is virtually always a model to sell products and then ignore them."*. Circular business aim to balance People, Planet and Profit, resulting in relatively new concepts like selling services instead of products:

Services engineering

More and more companies offer services with their products. For example "mobility-as-a-service" means a shift in the earning model. Previously a car manufacturer was interested in selling as much big cars as possible for a competitive price and lowest production costs to maximize earning. If this manufacturer now offers mobility as a service, he will be interested in transporting as much people as possible with a minimum of cars, having a high reliability, low energy consumption, and a long life span. So not the number of sold cars is the design driver anymore, but the higher quality of a smaller number of produced cars. A number of service business models have been identified ranging from classical product oriented selling to delivery of complete performance services (see Ref [26]) where a guaranteed performance and costs for the customer is delivered. Generally speaking these types of new services can contribute to sustainable systems.

End-of-life value

Circularity introduces new business: waste becomes residual value, and end-of-life products contain a value on materials and reusable parts. The end-of-life value of retired systems will well increase if the parts and materials can be properly reused or recycled, which means someone else wants to pay for it. Life Cycle Costing techniques can take this into account. It means that at business level the trade-offs must be made to maximize the value of products at the end of the life cycle through proper choices for remanufacture/reuse/recycling, and by establishing the required supply chains.

Innovation

Sustainable systems require new technology. This must be developed and proved ready for implementation. The SE process should balance the new technology risks and feasibility on a system development project and facilitate the proper trade-offs. Business and process innovation is also necessary: new business models arise as said before. New disciplines are entering the design process, for instance the chemical, bio-engineering, and environmental engineering disciplines. New tools are required to facilitate new techniques such as Design-for-X and LCA.

Consequences for Systems Engineering at business level

A number of consequences for Systems Engineering at this level are:

- Systems engineers must have a knowledge of services engineering, especially the relation between product quality parameters and the service performance parameters. A product family approach may support the services business model and sustainability. It provides flexible solutions and facilitates reuse and increased compatibility of parts. Important engineering parameters in this regard are Reliability and Availability, Economic Life, low Life Cycle Costs, and Adaptibility (resilience).

- Circular business models require implementation of the Design-for-X techniques mentioned before. Ref.[27] presents an extensive list of Design-for-X techniques and circular business models, as well as a relative mapping between these two.

- Process innovation and new tools is required due to integration of LCA, Design-for-X and new disciplines like for instance chemical, bio-engineering, and environmental engineering.

The business level defines the performance requirements, cost- and risk targets, the trade-off criteria and the criteria for recycling, reuse, remanufacture. These depend on the role the business takes in relation to other businesses as part of supply chains/circles and in competition with others. Business opportunities define these criteria, and those opportunities come from the next level: the industrial level. Furthermore a business also needs directions, regulations and standards, to keep a level playing field in competition with other businesses, also initiated in the industry level.

Level 4 – Industrial level

At the industry level the interactions between companies and organizations become apparent resulting in creation of business, competition, creation of standards and initiating innovations. This results in two concepts related to sustainability: circular economy and system of systems.

Circular economy

The circular economy is defined as: '*The circular economy describes human value systems which minimize waste by repurposing byproducts and discards. The unwanted outputs of one value chain become the feedstock of another, or are fed back into the original system, creating loops*', Ref.[2]. Systems contain products that represent value. The more complex the system, the more value it represents, but also reuse, remanufacture and recycling can become more complex. In the circular economy eco-design (minimizing negative environmental impact) changes into circular design by adding the concept of maximizing value so that sustainability is improved, Ref.[22].

Firms depend on each other for exchanging materials, flows and goods. Example: the heat wasted in one system can be used in another. These relations in the supply chain must be identified and supported, which means engineering at the system of systems level. Logistic networks need to be redesigned to accommodate recycling, remanufacture and product return and reuse. This is far beyond traditional logistics. So sustainability requires engineering and optimization beyond the System of Interest. It is only at system-of-systems level that sustainability can be achieved. Ref. [28]. The circular economy leads to new commercial inspired design choices that stimulate sustainability. Ref [33] provides a methodology to evaluate next product life cycles for new business opportunities.

System of systems

The concept of Systems of Systems means that systems are interacting with other systems and produce characteristics (emergent behavior) that is not visible if only one system of interest is looked at. This becomes relevant when sustainability is considered. Figure 5 illustrates some relationships between systems in the area of sustainability. It shows that the system of interest gets new relations with the ecosystem, the engine delivery system, supply chains, recycling system, economic system and the political system. Systems which normally have no relation show, when looked at in combination, emergent properties like global warming, less bio-diversity, water shortage, and so on.

Another characteristic of systems of systems are feedback mechanisms. In a study on systems thinking in Life Cycle Sustainability Assessments (LCSA) Onat et.al., Ref.[21], found that out of 56 studies only 2 studies utilized a "*complete systems thinking approach encompassing feedback mechanisms and interconnections (such as indirect effects, the dynamic relationships among social, economic, and environmental dimensions, market mechanisms, etc.) among the system of interests*".

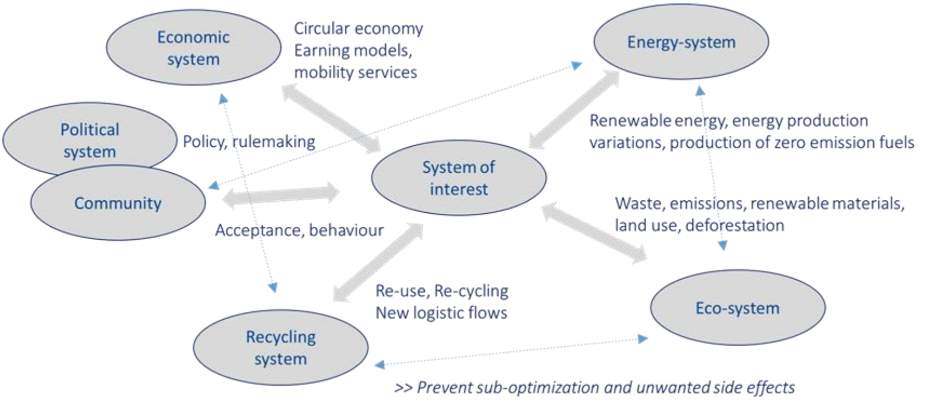

Figure 5. System of systems with sustainability relations

They say that the scope of the traditional LSCA studies (in itself a result of systems thinking) is predominantly at product level and does not address macro-level impacts and cannot capture a majority of upstream impacts due to narrowly defined system boundaries. They also conclude that "*A strong understanding of systems thinking is essential for the LCA community as well as decision-makers from industries and government organizations*".

Some aspects of sustainability require specific management of SoS. At the moment the developments in clean technology and renewable energy are fast and diverse. Renewable energy developments take place in various areas of research such as hydrogen, synthetic gas, bio-fuels, and energy storage. Various technologies are in different stages of maturity. All these developments require different systems for production and distribution. There is continuous change, because of new systems life cycles. These developments are more or less independent developments: at the moment there is not much coordination and no central management. The development of standards, attention for interfaces and dynamic effects can help to better guide these developments.

Consequences for Systems Engineering at industrial level

A number of consequences for Systems Engineering at this level are:

- The System of Interest extends outside the traditional system boundaries so engineering is required to design according to the opportunities of the circular business. Many optimizations and design choices should be made on the higher systems-of systems level. An optimum design for the system of interest is not the optimum for the system of systems. For the systems engineer it is important to recognize this and to prevent sub-optimization and unwanted side effects.

- Feedback effects over system boundaries are to be given proper consideration.

- Verification: on business level there are schemes available for verification and certification of business performance on sustainability, sometimes used in procurement. Some examples are: railsponsible.org, Green Business Certification Inc. (GBCI), http://www.gbci.org/, Cradle-to-cradle certification.

- Configuration Management and traceability become very important because the parts and materials which are reused or recycled will need to meet certain quality requirements, in order to be used again in new systems. For example aircraft structure materials or parts must meet stringent quality requirements, otherwise there use in an aircraft is not allowed. Another example is the quality assurance of new techniques such as 3D-printing. The article of Ref.[24] shows that new requirements for information exchange over the supply chain results from environmental regulations (REACH), leading to additional administrative challenges. So information on products and materials must be managed and kept up-to-date over subsequent life cycles, and handed over between owners.

The industry delivers services to the society, and these services increase wealth and create jobs. The industry can also have negative effects on society like unemployment, child labor, diseases, using up the earth resources, climate change, deforestation and so on. These are in fact combined effects of the small effects of individual businesses. What are the mechanisms that cause these combined effects? Industry is guided by law, regulations, public needs, and financial incentives: things that are created by the next level, the socio-economic level.

Level 5 – socio-economic level

This socio-economic level, which is in itself a systems of systems, includes the behavior of social systems, political systems and economic systems. Here the drivers are defined for industrial development: the public, the financial system and related incentives, laws, political decisions. For instance, the European Union has developed and instituted several regulations and guidelines on sustainability, among which the EU Action plan for the Circular Economy (2015), the Ecodesign directive (on energy labelling of products), and Guidelines for green procurement with the so-called GPP (Green Public Procurement) criteria for a wide range of products and materials, including verification methods. As an example, the GPP criteria for passenger cars contain a set of criteria such as CO2 emissions, exhaust gas emissions, requirements for systems to stimulate eco-driving, for oils, noise, alternative fuels and the use of materials. Criteria like these can help public procurement organizations for their contract requirements specifications. More details can be found on the EU website.

In Political and social systems emotions play an important role. It is therefore that Ref. [23] suggests that it is necessary to make planet values attractive for people. Organizations will not change fast, it requires effort and time, and pressure from outside can help such as attractiveness, social acceptance, rulemaking, and financial incentives. Many companies already use their policy on sustainability as a competitive advantage to other companies.

A good example of system of systems that is moving from one state to a completely new state is the energy system, in its transition to a completely renewable energy supply. It includes the development (and not to forget maintenance) of several parallel energy streams each consisting of systems for harvesting, energy conversion (to provide optimum fuels), energy storage and distribution. Ref.[30] gives a good explanation of the options for several energy schemes. Some driving design trade-offs in these new energy systems are: sustainable fuels for transportation and for the heat demands in heavy industries; optimum methods for energy storage to cope with the variable energy production of wind and solar power (see also Ref.[25]); optimum solutions for the transportation of energy from remote areas (wind and solar farms) to populated areas; continuous balancing of electricity supply and demand in a situation with widely distributed small and independent energy suppliers, in which the Internet of Things may play a dominant role. A true System of Systems! However in many studies the “enabling systems” are not addressed always: how to realize and maintain the infrastructure, transport and storage facilities of the vast amounts of electricity or hydrogen, including the required manpower, skills and knowledge. And the situation is changing rapidly: technology development is going fast, to name a few: the production of synthetic gas and fuels from CO_2, bio-fuels, and electricity storage methods. Ref.[29] shows several challenges to SE for the energy transition: conducting SE at the Sociopolitical level, gaining acceptance of SE in the energy related industry, and providing the necessary numbers of qualified systems engineers. The article gives also some examples of System of Systems methods which are necessary: development pathway analysis, transition scenario analysis, techno-economic analysis, and life cycle analysis.

An application of systems engineering tools (MBSE) in SoS is illustrated in Ref.[31]. This article presents a system of systems framework for the future hydrogen based transportation economy. The challenge for the SoS experts is how to design and implement a smooth transition from a petroleum based transportation system to a hydrogen based transportation SoS. They used MBSE (using CORE) for this SoS transition, by modelling a number of views from which the interactions between the physical system, the development system (WBS, planning, costs) and the external systems could be analysed.

Consequences for Systems Engineering at socio-economic level

A number of consequences for Systems Engineering at this level are:

- Sustainability requires System of Systems engineering techniques to be applied at the socio-economic level. This includes engineering of SoS variants including their enabling systems, interactions/feedback effects, and analysis of transition scenario’s. Financial, social and environmental effects need to be taken into account, and generated by disciplines unfamiliar to traditional systems engineers such as ecology, geographic, economic, and social disciplines, Ref.[9].

- Sustainability requires System of Systems management, which means managing interactions between independent development programs, without central authority. Systems Engineers should be able to generate, structure and integrate the required information to enable trade-off and decision making on this level.

- Because of the complexity of sustainability issues MBSE can play a role, but needs to be developed further extensively to accommodate the required views and discipline models, system parameters (especially the non-technical), feedback mechanisms, effects on the eco-system, socio-economic effects, and interactions within the SoS elements.

Summary and conclusions

The existing SE processes as described in the SE handbook and ISO15288 are perfectly suited for designing sustainability into the system. Sustainability engineering can be seen as a “specialty engineering discipline”, as is also stated in the INCOSE Vision for 2025 Ref.[9]. This discipline can be integrated into the SE processes, like any specialty discipline, by defining the sustainability requirements, evaluating designs on sustainability performance (using Life Cycle Analysis), making trade-offs, introducing design-for-X techniques, and by providing evidence for verification and validation. These would be good additions to the next issue of the INCOSE systems engineering handbook. This process is summarized in the Figure 6 below.

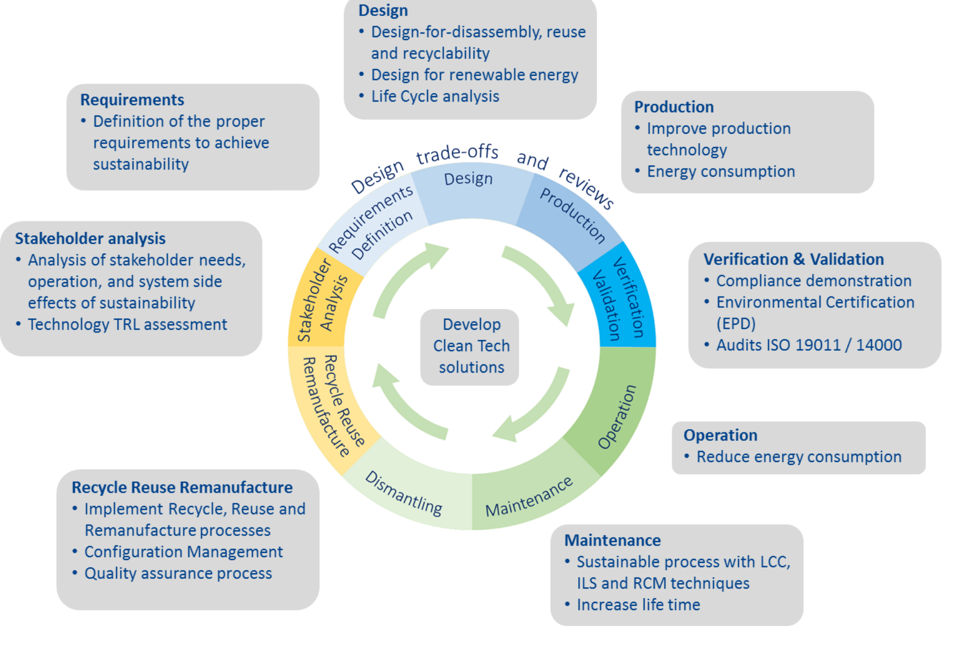

Figure 6. Sustainability Engineering roles in the SE process

But there is more. Achieving true sustainability in systems is a complex task which involves a collection of design techniques and trade-offs which in many cases exceed the boundaries of the system of interest. This is new for the Systems Engineering discipline:

- The value of disposables must be maximized – waste does not exist but is valuable input for new or next generations of systems.
- The business sustainability objectives, and the opportunities in a circular economy, must become the drivers for the right design choices (system architecture) and acquisition process to enable reuse/remanufacture/recycling.
- Engineering beyond the boundaries of your System of Interest is necessary – optimization for sustainability takes place at system of systems level.
- System Trade-offs and Life Cycle Analysis become more complex.
- New disciplines (such as ecological, biological, chemical, economic and social disciplines) need to be integrated into the SE process.
- Configuration and information management need to be extended beyond the life cycles and between companies.
- At the socio-economic level laws, rulemaking, permits/licensing, economic incentives (taxes) and public behavior are presently main obstacles for achieving sustainability. These aspects need to be considered in the systems engineering process when engineering for sustainability.
- Sustainability requires engineering and management on System of Systems level. The circular economy and energy transition are examples. These are typical dynamic, rapidly evolving systems of systems with no central authority.
- As a start, a sustainability plan or recycling plan (as part of the SEMP) should be made in every development project, planning the process and resources needed to realize a sustainable system.

This paper may prove that sustainability is not just another trade-off parameter which can be traded against others. Sustainability is not “more or less environmental friendly” which is called eco-efficiency. Instead, an eco-effective system is to be considered a new goal, meaning that during and after operational use, the waste, products and materials become valuable inputs for making new products and systems. This means real systems engineering and integration of all five system levels and related disciplines, otherwise it won’t work.

This paper has addressed a number of areas where more work is necessary to further develop the necessary knowledge, processes and tools to engineer sustainability.

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