Chapter 12
Systems Engineering

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Abstract The value of systems science approaches to address sustainability topics has been formally recognized since the publication of *Limits to Growth* (1972) and the application of system dynamics to investigate the synergies between planetary activities. Since then, these methods have been applied to address the chaos and reverse the consequences of the anthropomorphous influences at the root of today's wicked problems – climate change, species extinction, unbalanced social equity. Systems engineering provides theory and practices that are both systemic, systematic, sustainable, and based on the foundations of systems science.

12.1 Background

The purpose of this chapter is to describe the use of systems thinking and systems engineering for the purpose of addressing and working with sustainability challenges, dealing mainly with society-business interactions. Readers should note that the methods presented in the CapSEM Model (Part I, Chap. 2) focus mainly on environmental aspects of sustainability. Systems engineering provides a framework to fully consider the needs of stakeholders and other social and economic aspects (Fet and Knudson 2021).

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12.1.1 Definitions

Systems engineering (SE) is recommended as an approach to incorporate stakeholder needs and participation in the transition to sustainable and environmental management. SE is both a discipline and a process. As a discipline, SE concerns adopting a holistic life cycle perspective and constantly evolving to bring in aspects from other disciplines when needed. SE as a process is a *transdisciplinary and integrative approach* to enable the successful realization, use, and retirement of engineered systems – both technological and social, by using systems principles and concepts, and scientific, technological, and management methods (Sillitto et al. 2019). The *transdisciplinary approach* organises the analysis and decision-making around common purpose, shared understanding and 'learning together' in the context of real-world problems or themes. It is usable at any CapSEM Level, from simple to complex, and is especially necessary in unprecedented situations or where there exists a significant degree of complexity. An *integrative approach* by itself can be adequate where the situation is not overly complex or when dealing with a situation that has been encountered before and a path to the solution can be readily identified and understood (albeit there will still be many challenges along the way, technical and otherwise). Systems principles and concepts are the ways in which systems thinking and the systems sciences provide a foundation for systems engineering practices. Examples of some of the principles, concepts and supporting tools are mental models, system archetypes, holistic thinking, separation of concerns, abstraction, modularity and encapsulation, causal loop diagrams, systemigrams, and systems mapping. The Systems Engineering Body of Knowledge (SEBOK 2021) describes many of these: it also provides an extensive reading list.

12.1.2 SE Practices

Two concepts are essential to understanding the broad scope of systems engineering. The first, systematic, means taking a thorough, orderly approach to solving a problem or set of problems. The second is the systemic perspective. The term means taking a holistic appreciation of the topic under consideration, whether a man-made engineered system or an international political effort toward reduction of climate gases emissions. The literature of systems engineering practice describes a variety of systematic processes for developing, designing, and deploying large-scale complex systems, such as the standard for systems engineering life cycle development ISO/IEC/IEEE 15288: 2015. At the same time, successful systems engineering must be built on a foundation of systemic thinking to conceive and solve complex problems (Hitchins 2007).

Systems engineering can be used as a management technology to assist and support policy making, planning, decision making, and associated resource allocation or action deployment. All systems engineering may be thought of as consisting of formulation, analysis and interpretation of the various elements in all phases of the life cycle of a system. Both top-down and bottom-up approaches are needed and used in SE practices. The top-down approach is primarily concerned with long-term issues that concern structure and architecture of the overall system and is useful in planning phase when the system must be viewed as a whole, as at CapSEM Level 4. The bottom-up approach is concerned with making parts of the system more efficient and effective so they can be incorporated into the overall system and is useful when determining the tasks to support operational decisions, as in CapSEM Levels 1–3 (Fet and Knudson 2021).

12.2 Description

Systems engineering as a process to support planning, decision-making and system design has been described in many ways to address the unique needs of a given situation or domain. Fet (1997) devised a generic process that encompasses the essential activities of the SE development life cycle process. This 6-step model is provided in Fig. 12.1 and is the basis for the mapping to relevant CapSEM methods presented in Fig. 12.1.

Step 1: Identify Needs
In this step, the stakeholders' needs, their values and concerns are identified. It includes an iterative loop where the statement of needs answers the question *What is needed?* The logic is an answer to the question *Why is it needed?* and the search for preconceived (technical) solutions answers the question *How may the need be satisfied?* The *statement of need* should be presented in specific qualitative and quantitative terms, in enough detail to justify progression to next step.

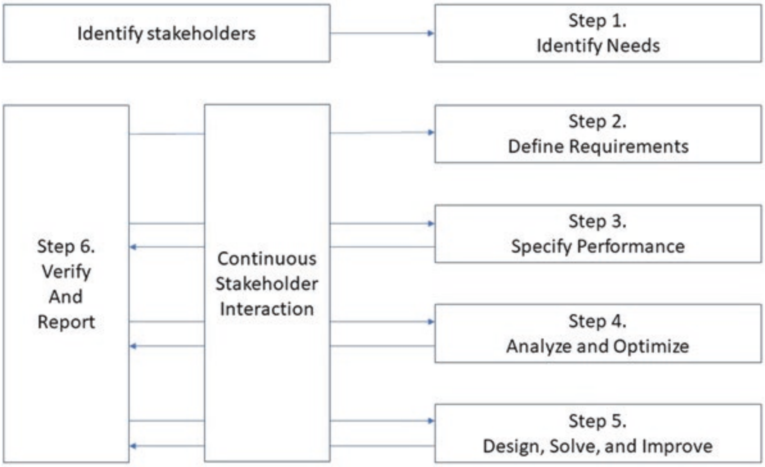

Fig. 12.1 Systems engineering life cycle process, 6-step framework

Step 2: Define Requirements

After identifying stakeholders' needs, attention turns to defining requirements that describe how the system is supposed to be designed, function and be operated during the life cycle. Both functional, operational and physical performance requirements should therefore be defined. While functional requirements reflect the system's ability to carry out functions and should be an answer to the *what* in step 1. Operational requirements are related to the operation of the system all in a life cycle perspective, and an answer to the *why* in step 1. The physical requirements reflect the physical conditions the system will be exposed to, and how the system interacts with the environment, and thereby an answer to the *how* in step 1. The definition of functional, operational and physical performance requirements must be set to each of the integrated parts of a system, both to the hardware, software, bioware and the economic parts, which together describe a system (Fet 1997).

Since the toolbox in the CapSEM Model mostly concentrate on the environmental issues of sustainability, the defined requirements should also take a specific role in meeting the performance requirements for achieving the change in performance as was illustrated in Fig. 2.1 in this book. By identifying relevant SDGs that points to the actual CapSEM-levels as shown in Fig. 3.2, the underlying targets can be helpful when specifying the necessary performance requirements to meet the stated needs under step 1.

Step 3: Performance

As soon as the system requirements are defined, they should be translated to performance specifications, i.e. definable and measurable performance criteria. The specification of performance should be formulated by means of performance indicators, for example, OPIs, MPIs and KPIs, and reflect the needs and requirements formulated in Steps 1 and 2, and also help to answer *What*, *Why* and *How*.

The functional analysis should be performed as an iterative process to ensure that all elements of system design and development, production, operation, and demolition and support are covered in the performance specification. The performance should be specified in a way that measurements verify that needs and requirements are met. Quantification of the performance indicators selected in step 3 are further analyzed using impact assessment methods and other various tools suggested in the CapSEM Model such as life cycle assessment (LCA) and material flow analysis (MFA) (Valenzuela-Venegas et al. 2016).

Step 4: Analyze and Optimize

System analysis includes an analytical process of evaluating various system design alternatives. This is called a *trade-off* which may be defined as "a compromise between conflicting interest with the need to maintain equilibrium" (Rolstadås 1995). This step includes activities such as searching for a configuration, principles and technologies to meet specifications conceptually, selection or discrimination between system alternatives, and optimizing by the trade-off analysis. Trade-offs between many, often conflicting system requirements, should be carried out, and this analysis of the system and the specification of its performance goes into an iterative loop of improvements.

The problem is to select the best approach possible through the iterative process of system analysis using various analytical methods. The use of weight factors based upon the priorities of stakeholders is an important part of the analysis (Freeman 2010). Different optimization techniques should be used.

The trade-off therefore needs to meet a few requirements itself. These may be:

- Define the objective function for the total system performance evaluation
- Define the conditions under which the system performance is to be measured
- Establish the measurement/evaluation criteria for a ‘best’ satisfaction of the functional, operational and physical needs and requirements.

In the optimization phase it is important to select objective functions taking all alternatives into account. The general purpose of an objective function is to express in quantitative form a total single measure of the system performance. Performing the analyses, optimisation and evaluation is again an iterative process and should be performed until a design (or suggestion to the solution of the problem) is accepted.

Step 5: Design, Solve and Improve

Based on the preliminary system design or suggestion of solutions, a detailed design phase begins derived from the preliminary needs through system requirements and performance specifications, synthesis and analysis. When the overall system definition has been established in an accepted conceptual solution, it is necessary to progress through further definitions leading to the realization of hardware, software, bioware and economics, all seen in relation to their possible environmental impacts throughout the system’s life cycle. Decision-makers should make the final decision on which changes to implement. Where multiple strategies exist, decision-makers may use multi-criteria appraisals to identify preferred strategies based on the stakeholders’ subjective preferences with reference back to stated needs and requirements.

Step 6: Verify and Report

The final step of the process concerns monitoring and recording the performance of the selected course of action. The iteration between steps 4 and 5 should provide the information and data needed to continuously evaluating the current strategies and come up with solutions for improvements and changes to the actual CapSEM Levels.

12.3 Application

Progress toward environmental and sustainability performance improvements at different system levels is encapsulated in *human activity systems*. The term refers to social systems where the intentional agents are humans, working toward a common purpose and where the social system is deliberately constructed and maintained and can adapt rapidly. A major goal of Systems Engineering is to reduce the risk that accompanies such systems by establishing shared and valid models of the system, in order to improve stakeholders’ knowledge and understanding of the system and its context. To quote Forrester, the inventor of System Dynamics,

> We do not live in a unidirectional world in which a problem leads to an action that leads to a solution. Instead, we live in an on-going circular environment. Each action is based on current conditions, such actions affect future conditions, and changed conditions become the basis for later action. There is no beginning or end to the process (Forrester 1998).

12.3.1 Systems Approach for Capacity Planning

In his insightful article on how capacity planners can benefit from systems thinking, Hauck (2005) offers the following five insights:

- Cause and effect relationships are not always linear; they are frequently delayed in time and unpredictable
- Many successful systems have evolved through incremental adaptations
- Many capacity development processes do not have measurable objectives, but are guided by implicit intentions and ideas that adjust to emerging situations
- Interconnections among the components of a system are important and can give rise to valuable synergies
- Feedback is critical for learning and self-awareness, but the form it takes is culturally determined and cannot be applied in a standardized manner.

These insights are relevant to decision-making throughout the entire life cycle of a system and can be applied from decisions at Level 1 and at each subsequent level of the CapSEM Model. Systems approaches such as these have become standard practice for monitoring progress of the current UN sustainable development goals (Selomane et al. 2019; Haskins 2021). Levels 1 and 2 concern technical analysis. Levels 3 and 4 mainly concern human decisions between people, technology and an organization.

12.3.2 Systems Engineering applied to the CapSEM Model

To illustrate the usefulness of SE as a framework for choosing methods for implementing the CapSEM Model approaches to sustainability, Fig. 12.2 maps the basic SE process in the left column to the activities and outcomes for the recommended methods including Level 1, represented by cleaner production (CP), Level 2, represented by life cycle assessment (LCA) and design for the environment (DfE), Level 3, represented by environmental management systems (EMS) and environmental performance evaluation (EPE).

The application of SE practices to a given CapSEM method also requires attention to the topic of system boundaries (step 1), which occur between (1) the system under study and the environment, (2) the system under study and other interrelated systems, and (3) relevant and irrelevant processes (Selomane et al. 2019). Material, energy and information crossing the boundaries are defined as inputs to or outputs

Systems engineering (SE)	Cleaner production (CP)	Life cycle assessment (LCA)	Design for environment (DfE)	Environmental management systems (EMS)	Environmental performance evaluation (EPE)
1. Identify needs	1. Planning and organising	1. Goal and scope definition	1. Needs analysis	1. Environmental policy	1. Commitment
2. Define requirements			2. Requirements	2. Initial planning	2. Planning
3. Specify performance	2. Assessment and preparation	2. Inventory analysis		3. Planning 4. Implementation and operation 5. Checking and corrective action	3. Applying
4. Analyse and optimise	3. Assessment step 4. Feasibility analysis step	3. Impact assessment 4. Interpretation	3. Life cycle strategies and evaluation		
5. Design, solve and improve	5. Reporting 6. Implementation	Application of LCA results	4. Design		4. Reviewing 5. Improving
6. Verify and report			5. Implement	6. Management review 7. Documentation 8. Registration	

Fig. 12.2 Mapping of systems engineering processes to CapSEM Model methods and tools (Fet 2002)

from the system. As part of an environmental analysis, the environmental loads are determined by materials extracted from natural resources and emissions into the environment, all of which cross defined system boundaries. Processes often generate different products, byproducts and functions, in co-production, recycling or waste processing. System interactions should be classified according to which of the interrelated systems belong to the system under study, and which do not. Only after selecting the most appropriate system boundaries can the decision be taken of how the scope of a given study of a system should be extended.

12.3.3 Systems Engineering as an Integrating Framework

The eventual application of SE in any CapSEM Level relies on integrated practices as recommended by Asbjørnsen (1992). A system should be viewed as a combination of some or all of four different disciplines of roughly equal importance:

- the disciplines of technology that include the physical equipment (Hardware),
- the disciplines of financial science that include the monetary aspects (Economics),
- the disciplines of information science that include computer applications (Software),
- the disciplines of social science that include human factors and psychology (Bioware).

In this way, technology, management, legal aspects, social and environmental issues, finance and corporate strategies are all addressed by a total system integration and inter-disciplinary cooperation. Decisions made during the early phases of system development have a great impact on the total life cycle costs, as well as the life cycle environmental performance. Both the life cycle costs and the life cycle environmental performance should be balanced against the estimated improvement in performance and related to the overall purpose of the system. In addition, the processes and methods utilized in the acquisition of systems must be such that systems can be acquired in a timely and expeditious manner and designed and developed as effectively and efficiently as possible, considering the limitation of available resources. The resource requirements and the time requirement to carry out and complete the work must be specified early in order to ensure a proper allocation of resources, and to relate the work properly to the total time available, e.g., an upgrade to a manufacturing facility will desire the shortest possible downtime.

12.4 Systems Engineering as a Collaboration Framework

Sillitto et al. (2019) assert that SE is essentially collaborative in nature, facilitating collaboration between all contributors to system success, recognizing the need to respect diverse points of view. They suggest the following critical activities supported by SE practices (Sillitto et al. 2019).

- Defining and managing the interfaces, both within the system and between the system and the rest of the world (noting that increasingly, systems engineering is conducted in a brown-field rather than a greenfield environment, so legacy systems may be a major or key part of the overall solution);
- Establishing appropriate process and life cycle models that consider complexity, uncertainty, change and variety, and implementing system management and governance processes for both development and through-life use and disposal;
- Supporting transition to operations, considering all aspects including people, processes, information and technology;
- Periodically re-evaluating status, risks and opportunities, stakeholder feedback, observed or anticipated unintended consequences, and anticipated system effectiveness and value, and recommending any appropriate corrective, mitigation or recovery actions to ensure continuing system success.

These can include upgrading, obsolescence management, maintenance and repair activities, manufacturing changes, changing operational processes, user training, instituting metrics and incentives, assessing information quality and integrity, and making other changes to the system as suggested by the CapSEM Level and methods employed.

12.5 Conclusion

This brief introduction to SE gives an overview of systems engineering practices in regards to their position(s) on the CapSEM model, explaining the contribution of these activities and their relevance to all Levels of the model. The reader is encouraged to explore the references given here as a departure point for employing these methods.

References

Asbjørnsen OA (1992) Systems engineering, principles and practices. Skarpodd, Arnold

Fet AM (1997) Systems engineering methods and environmental life cycle performance within ship industry. Norwegian University of Science and Technology

Fet AM (2002) Environmental management tools and their application – a review with references to case studies. In: Conceição P, Gibson DV, Heitor MV, Sirilli G, Veloso F (eds) Knowledge for inclusive development. Quorum Books, Westport, pp 451–464

Fet AM, Knudson H (2021) An approach to sustainability management across systemic levels: the capacity-building in sustainability and environmental management model (CapSEM-model). Sustainability 13(9):4910. https://doi.org/10.3390/su13094910

Forrester JW (1998) Designing the future. Transcript of lecture delivered to Universidad de Sevilla, Spain, December 15, 1998

Freeman RE (2010) Strategic management: a stakeholder approach. Cambridge University Press

Haskins C (2021) Systems engineering for sustainable development goals. Sustainability 13(18):10293. https://doi.org/10.3390/su131810293

Hauck V (2005) Applying systems thinking to capacity development. Capacityorg 26:16

Hitchins DK (2007) Systems engineering: a 21st century systems methodology. Wiley, Chichester

Rolstadås A (1995) Performance management, A business process benchmarking approach, Chapmen & Hall, UK.

SEBoK Contributors (2021) Principles of systems thinking. In Systems engineering body of knowledge, https://sebokwiki.org/wiki/Principles_of_Systems_Thinking. Accessed 15 June 2021

Selomane O, Reyers B, Biggs R, Hamann M (2019) Harnessing insights from social-ecological systems research for monitoring sustainable development. Sustainability 11(4):1190. https://doi.org/10.3390/su11041190

Sillitto H, Martin J, McKinney D, Griego R, Dori D, Krob D, Godfrey P, Arnold E, Jackson S (2019) Systems engineering and system definitions. In INCOSE-TP-2020-002-06 | 22 July 2019. https://www.incose.org/docs/default-source/default-document-library/final_-se-definition.pdf. Accessed 27 June 2022

Valenzuela-Venegas G, Salgado JC, Díaz-Alvarado FA (2016) Sustainability indicators for the assessment of eco-industrial parks: classification and criteria for selection. J Clean Prod 133:99–116. https://doi.org/10.1016/j.jclepro.2016.05.113