# Thinking Tracks for Integrated Systems Design

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**Summary:** The paper investigates systems thinking and systems engineering. After a short literature review, the paper presents, as a means for systems thinking, twelve thinking tracks. The tracks can be used as creativity starter, checklist, and as means to investigate effects of design decisions taken early in the process. Tracks include thinking about time, risk and safety, and different types of life-cycles. The thinking tracks are based on literature, teaching experience and practice as a system designer. By using the tracks a more complete picture of the system under design, the issue to be solved, the context, stakeholders and the rest of the world is created.

Keywords: System, System Architecture, Design, System Engineering.

## 1. Introduction

Systems engineering has a long history that, one can argue, dates back to Noah's Ark, the Pyramids, Aqueducts and Roman road systems. A huge development in the systematic approach of systems engineering (SE) took place around the second World War in military disciplines and shipbuilding. The result is a welldocumented process that is described in for instance the INCOSE (International Counsel on Systems Engineering) handbook [1], the excellent book by Blanchard and Fabrycky [2], and the book by the respected experts A.P Sage and J.E. Armstrong jr. [3].

On the other hand, systems *design* requires more than this systematic work. There is a need for a freer mind-set that is directed at creating products that deliver value for all stakeholders involved. This *architecting* process is by its very nature less systematic, and sometimes called an art. One of the important works in this field is The Art of Systems Architecting by Maier and Rechtin [4], where a heuristic based approach is taken to define the systems architecture. A more recent work is Gerrit Muller's Systems Architecting – A Business Perspective [5], that is somewhat more systematic, and based on frequent viewpoint hopping, many visualisations, modelling and short iterations (to name a few).

In all cases the essence of systems design is to identify an issue, this can be a space mission, a market opportunity, the need for less fuel consumption etc., and find a system that fits that issue. Often finding the issue and defining the solution go hand in hand – but they should not be mingled. However, the two cannot be seen in isolation. There are stakeholders (often many) involved, and the issue and system under design (SUD) have to fit a context. And even when these are well known, there is the rest of the world: the context is open, see Figure 1.

The systematic SE process as described in [1-3] may ensure proper fit between the known identified issue, context and stakeholders, but it may fall short when the unknowns have to be met. The less formal processes in [4, 5] do provide the means to take these unknowns into account, but more is needed: means for system thinking. This paper, will explore such means. First, after the above concise state of the art of systems engineering, section 2 looks at system thinking, and defines a number of needs for thinking tools. The main part of the paper is section 3, where, based on earlier work from literature, teaching experience at the University of Twente and practical experience from the author, we will present a number of thinking tracks that can help the system designer. Section 4 closes the paper with a discussion.



**Figure 1.** The System under Design (SUD) has to fit an identified issue, the context, stakeholders and the rest of the world. The curved path shows one of –many– possible thinking tracks presented in this paper.

## 2. System thinking

A system is "a set of interrelated components functioning together toward some common objective(s) or purpose(s)" [2]. Thus, designing systems involves thinking about relations, functions, purpose, objectives, a set or sets. Also, the creation of all these has to be considered. Referring to Figure 1, the context, stakeholders, and rest of the world must be kept in mind. In addition, as nothing is completely new, and most goods have a life cycle of years, time must be regarded.

Systems thinking tools should support the system designer(s) in considering these aspects, and help him/her to oversee the consequences of his/her decisions. [6] Presents an overview of the profile of potential system thinkers. The

overview also is a basis for system thinking tools. Distilling the needs for thinking tools from the above-mentioned paper results in:

- Showing the Big Picture;
- Understanding connections and closed loops;
- Understanding synergy;
- Looking from multiple perspectives;
- Tolerate ambiguity and uncertainty;
- Propagating possible changes;
- Life-cycle analysis;
- Finding new solutions; innovation; creativity

In [7] the conceptagon is presented as a visualization of the different aspects of a system and its development organization. It shows that a system designer needs to switch viewpoints in order to come to a coherent system design and design for the production facilities. Muller mentions in [8] so called *threads of reasoning* for wandering through the system design, and through the system functions, and the application of the system in order to verify whether the system architecture is coherent.

#### 3. The system thinking tracks

In the remainder of this paper, we would like to extend the work done by Richmond [9] and present a number of thinking tracks that help the system designer in exploring and/or verifying the fit between SUD and issue, or SUD and context, or SUD and rest of the world. The tracks are in that sense concretisations of the abilities and competences presented in [6]. The tracks are not a replacement for the SE process, but a complement. They can be used as a checklist, as a creativity starter, as a means to avoid mental inertia by looking at the problem from different viewpoints, or for instance to fill the conceptagon [7]. They are a concretisation of Muller's threads of reasoning [8].

The tracks are of particular use in the early phase of design when far-reaching decisions are made based on limited information. Later, when more information is available there is limited freedom for changes. Then the thinking tracks can help in determining consequences of decisions and the value of information, albeit often not objectively and formally.

The tracks are presented very concisely as space is limited. In some cases an example is given, in other cases a few questions are presented that the system designer can ask himself or his colleagues.

## 3.1. Dynamic thinking

Look at the system from a dynamic or time-related perspective:

- How does the system change over time?
- How does the environment change over time?
- What are the effects of a change in input/output?

This should be analysed on different time scales ((milli-) seconds, minutes, hours, days, months, years, decades). It is wise to present the results in different ways and even in time domain and frequency domain.

#### 3.2. Feedback thinking

Is there feedback in the system? If not, why not? What is the output signal and what is the desired output value? Can it be measured? Is the response of the measurement system accurate enough and fast enough? What is the system to be controlled (the *plant*)? Are there ways to influence the plant (is it controllable)? Is a controller possible at all? What is the actuator?

This thinking track does not only apply to technical systems, it is very relevant in politics (but not used enough), social systems and even interpersonal relations.

## 3.3. Specific-generic thinking

Specific-Generic thinking is about the scale of the problem and the solution. Is the problem at hand so specific that only a specific solution is fit, or can a generic solution do the job? Is a quick fix acceptable, or is a universally applicable and thoroughly documented solution required?

This track can be well supported by modelling. Even simple order of magnitude models help here. A good set of examples is shown in [10] where it is applied to energy use.

#### 3.4. Operational thinking

A danger in system design is that the artefact remains abstracted in schemes and diagrams. Formalisms like SysML and UML do not show how an actual wafer stepper or medical image scanner work. Operational thinking investigates how the process is actually performed by showing it in:

- Storyboards/scenario's;
- Workflow diagrams;
- Drawings and sketches of the systems;
- Facility layouts, etc.

Operational thinking links the more abstract architecture to the details that matter and help to bridge the gap between the system designers and operators.

## 3.5. Scales thinking

Engineers are educated and used to working with exact and verifiable data. Yet in systems design uncertainty plays a large role. Scales thinking is understanding the difference between the yes/no-scale on the one side and a shades of grey-scale on the other, and the ability to switch between the two.

#### 3.6. Scientific thinking

This track emphasizes the need for verification, based on literature, experiments and/or simulations. Measurements need analysis of their accuracy and resolution. Experiments are therefore a part of the systems designer's toolkit and everyday work. As mentioned in section 3.3, modelling is a good tool and [10] uses it to prove or disprove many arguments in the energy field.

Note that an inherent problem in systems engineering *research* is that it is virtually impossible to do comparative *and* realistic case studies, due to the scale of realistic cases.

#### 3.7. Decomposition-composition thinking

Systems engineering is often presented as a means to decompose a system into smaller bits in order to facilitate the development process. The way to *compose* these bits into a working system is not given enough attention, yet it is a problematic part for many development projects. Decomposition-Composition thinking is a track that stimulates the system designer to think with each decision:

• How will we put this together?

- How to check whether this will fit and work before shipping?
- Is there a way to see whether a module is finished? Etc.

Interfaces and requirements management play a crucial role in this thinking track.

#### 3.8. Hierarchical thinking

In hierarchical thinking the system designer reasons about ranking control, authority, facilities and priorities over the system's parts. As an example: is there central control of the building temperature, or distributed control? Where is the heat generated? In every room, centrally in the building, or externally?

Related is the hierarchy in the organization. This is mostly not under the influence of the system designer, but the system designer should be aware of it.

#### 3.9. Project thinking

In many cases there is a relation between the architecture of the system that is created and the organization that creates the system. For a new organization, the organization may be shaped according to the SUD, but later on the system's architecture may have to adapt to the organization [11]. Awareness of the organization structure is essential for the system designer, a certain nonchalance here can help, too.

## 3.10. Life-cycle thinking

The life-cycle has to be considered in every decision. In this respect, three life-cycles can be understood:

- The product life-cycle from need via design, production, deployment, use to retirement;
- The resource life-cycle that describes how materials and energy are used and reused, and what the environmental impact is; and
- The project life-cycle that describes how the project organization that is put in place to develop, build and sustain the system, evolves.

An example for product life-cycle thinking: a decision that is beneficial in the use phase can have negative consequences in the production phase. Life-cycle thinking is there to detect these and to determine actions to accommodate the consequences.

## 3.11. Safety thinking

Product safety is paramount and many regulations exist. The product requirements state conformity with these. Yet, this is on system level. On lower level, the safety consequences of design decisions are not always clear, and vice versa the implications of the regulations cannot be overseen. With safety thinking we mean thinking about the consequences and their implications.

#### 3.12. Risk thinking

Designing innovative products and systems comes with risks by nature. Managing the risks is inherent to product development. Risk thinking should be done by every project member, more than all the other thinking tracks, as identification of a risk can only be done by the project member closest to the actual development. Risk management, in other words, what to do with an identified risk, is an established discipline that needs no space here.

#### 4. Discussion

The thinking tracks presented above are intended to wander through the space in Figure 1 in a chaotic path where the tracks complement each other to create a richer and more complete picture of the entire design environment. The thinking tracks need concrete tools to support them. Such tools are, for instance, the TRIZ 9-window diagram, context diagram, scenario's and storytelling, various ways of functional modelling, the N<sup>2</sup> diagram, architecture models, system budgets, FunKey architecting [12], Failure Mode and Effect Analysis (FMEA). Space prohibits a more extensive treatment of these tools. Also, the thinking tracks are only useful within a defined process context. The established SE processes described in [1-3] or the architecting processes [4, 5], to name a few, can be this context.

While SE is well established, system design or system architecting is relatively young as a discipline. In addition to the structure of these established SE process, system designers need ways to think through the design space. Although there are people who do this by nature, others need a form of guidance in this thinking. In this paper, we have presented twelve thinking tracks that can serve as checklists when designing systems. The link between the thinking tracks and the required skills for system thinkers as identified by [6] is easily made. Due to space, the tracks are treated concisely. A more elaborate treatment [13], including the support with tools, is at present used in lectures for systems engineering at the University of Twente.

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## References

[1] INCOSE SEH Working Group, 2008, Systems Engineering Handbook. 3.1 ed: INCOSE.

[2] Blanchard, B.S. and W.J. Fabrycky, 2011 Systems Engineering and Analysis. 5<sup>th</sup> ed, Upper Saddle River, New Jersey: Prentice Hall.

[3] Sage, A.P. and J.E. Armstrong jr., 2000, Introduction to System Engineering: John Wiley and Sons, Inc., New York.

[4] Maier, M.W. and E. Rechtin, 2000, The art of systems architecting.  $2^{nd}$  ed, Boca Raton: CRC Press.

[5] Muller, G., Systems Architecting, 2011, A Business Perspective, Boca Raton, FL: CRC Press.

[6] Frank, M., 2006, Knowledge, abilities, cognitive characteristics and behavioral competences of engineers with high capacity for engineering systems thinking (CEST), Systems Engineering, The Journal of the Intern. Council on Systems Engineering, 9/2:91-103.

[7] Boardman, J., B. Sauser, L. John, and R. Edson, 2009, The conceptagon: A framework for systems thinking and systems practice, IEEE International Conference on Systems, Man and Cybernetics (SMC 2009).

[8] Muller, G.J., CAFCR, 2004, A Multi-view Method for Embedded Systems Architecting, Ph.D.-thesis, Delft University of Technology

[9] Richmond, B., 1993, Systems thinking: Critical thinking skills for the 1990s and beyond. System Dynamics Review,. 9/2:113-133.

[10] MacKay, D.J.C., 2008, Sustainable Energy - Without the Hot Air, Cambridge: UIT.

[11] Gulatti, R.K. and Eppinger, S.D., 1996, The Coupling of Product Architecture and Organizational Structure Decisions., MIT Soal School of Management, Cambridge, MA.

[12] Bonnema, G.M., 2011, Insight, innovation, and the big picture in system design. Systems Engineering, 14/3:223-238.

[13] Bonnema, G.M., K.T. Veenvliet, and J.F. Broenink, 2012, Systems Design and Engineering - Lubricating Multidisciplinary Development Projects, Enschede: University of Twente.