MERGING SYSTEMS ARCHITECTURE AND PROJECT MANAGEMENT

In recent years, systems engineering (SE) is becoming more important in the Dutch high-tech equipment industry. Increasing system complexity and increasing team sizes put more emphasis on the explicit coordination of design activities. SE connects two worlds: the technical world with system models managed by the systems architect and the management world with process models managed by the project manager.

In the Dutch high-tech equipment industry, we are already used to these worlds closely collaborating.

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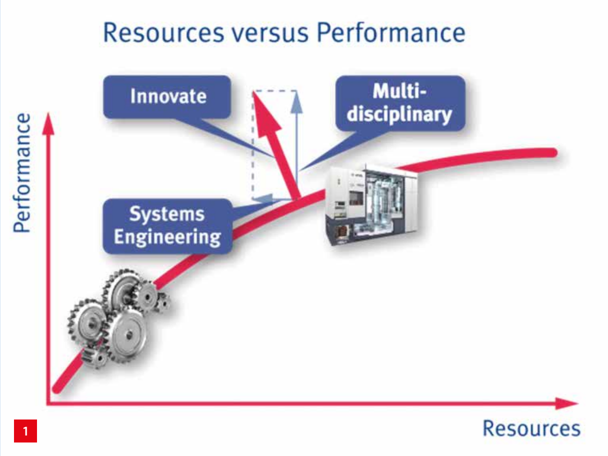
SE is defined in many ways. According to the International Council on Systems Engineering (INCOSE), “Systems Engineering is a trans-disciplinary and integrative approach to enable the successful realisation, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods” [1]. SE can be applied to technical systems, but more general to other kinds of systems as well, such as organisational systems, societal systems, etc., as a means of dealing with complexity (see Figure 1). SE relies strongly on systems thinking, which itself has many definitions. A practical one is “Systems thinking is the ability or skill to perform problem solving in complex systems” [2].

In general, Dutch high-tech companies use model-based development methodologies. Design teams are always multidisciplinary, mechatronics is one of the terms that is used to express this multidisciplinary character. The design teams use a design methodology that is based on models of which the detail increases as the design evolves. Starting out with simple, lumped parameter models to capture the most important performance-limiting interactions in the system under development, details are added when the design progresses. Many models are being developed, and not always do these models evolve over the full design cycle. Typically, a variety of models rooted in various technical disciplines are used, oftentimes including multi-physics models.

Never we use all-encompassing, all-physics models that can capture all relevant details for all phases of the design cycle. It is hard to conceive that such all-in-one models will ever become available for developing a system; however, visualising a full system will be possible.



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Dealing with increasing complexity. (Source: TU/e HTSC)

So, while our system design efforts critically depend on truthful models using correct parameters to efficiently develop effective and reliable engineering solutions, they must deal with many of these, often multi-physical models that each evolve over time in their own rhythm. The management of all these models becomes a severe challenge, especially for large and complex high-tech systems. Noting that the union of all the models captures all relevant aspects of the system we are developing, a single-source-of-truth (at a given moment in time in the design process) for all models becomes an important requirement.

Since the design of the whole system will require regular rebalancing of requirements and their allocation to the various subsystems, management of the models is a system-level responsibility. It is here that SE should have its key responsibility: SE should provide processes and a methodology to structure and coordinate model-based engineering. Novel developments in the world of SE

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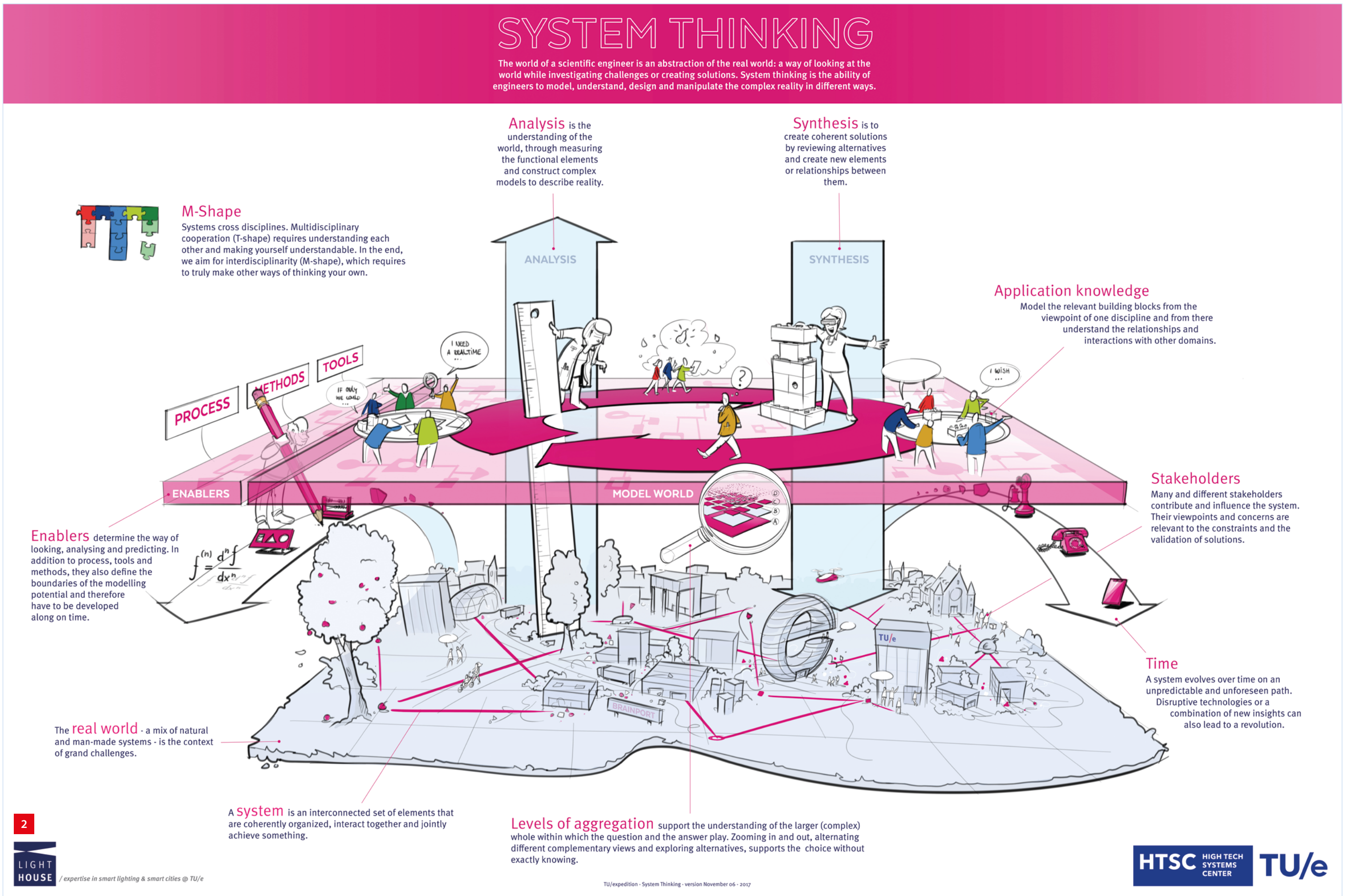

SYSTEM THINKING

The world of a scientific engineer is an abstraction of the real world: a way of looking at the world while investigating challenges or creating solutions. System thinking is the ability of engineers to model, understand, design and manipulate the complex reality in different ways.

Analysis is the understanding of the world, through measuring the functional elements and construct complex models to describe reality.

Synthesis is to create coherent solutions by reviewing alternatives and create new elements or relationships between them.

M-Shape
Systems cross disciplines. Multidisciplinary cooperation (T-shape) requires understanding each other and making yourself understandable. In the end, we aim for interdisciplinarity (M-shape), which requires to truly make other ways of thinking your own.

Application knowledge
Model the relevant building blocks from the viewpoint of one discipline and from there understand the relationships and interactions with other domains.

Stakeholders
Many and different stakeholders contribute and influence the system. Their viewpoints and concerns are relevant to the constraints and the validation of solutions.

Enablers determine the way of looking, analysing and predicting. In addition to process, tools and methods, they also define the boundaries of the modelling potential and therefore have to be developed along on time.

Time
A system evolves over time on an unpredictable and unforeseen path. Disruptive technologies or a combination of new insights can also lead to a revolution.

The **real world** - a mix of natural and man-made systems - is the context of grand challenges.

A **system** is an interconnected set of elements that are coherently organized, interact together and jointly achieve something.

Levels of aggregation support the understanding of the larger (complex) whole within which the question and the answer play. Zooming in and out, alternating different complementary views and exploring alternatives, supports the choice without exactly knowing.

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Systems thinking and systems engineering. (Source: TU/e HTSC)

organisations such as INCOSE are addressing this development under the term model-based systems engineering (MBSE).

Systems engineers and systems architects are working in close cooperation: in our definition a systems architect organises the design of a solution, especially at the sub-system and module level, such that a system can be built while a systems engineer is responsible for defining the constraints for the development such as properly articulating the requirements and coordinating the interfaces between the various sub-systems and modules.

Systems thinking

In a study group at Eindhoven University of Technology, the integration of systems thinking in education was discussed. As a result, the picture of Figure 2 was made. It shows the real world, in grey and at the bottom. In pink, a model representation of this world is drawn. In the centre is a magnifying glass that shows how this model world is a hierarchy of increasingly detailed models. In the model world, multidisciplinary teams of differently coloured engineers develop solutions for real-world problems, iterating between analysis and synthesis. In the analysis phase, the real world is measured and understood, as is the way in which real-world problems may be addressed. In the synthesis phase, solutions are engineered and deployed.

Ideally, the engineers have T- or M-shaped profiles, whereby in-depth understanding of one or two aspects (the vertical lines of a T- or M-shape, respectively) is combined with the ability to work with and understand engineers from other disciplines (the vertical lines of the shape). Aspects of application knowledge, stakeholders, enablers and levels of aggregation are also highlighted.

The Dutch 'secret sauce' to SE

Systems thinking in Dutch high-tech equipment design has evolved out of systematic analysis of mechanical design principles, as initiated by Wim van der Hoek, and the use of feedback control as an extension to those design principles. Feedback control was required to further improve accuracy and speed of equipment, and the control engineering discipline grew central to system performance and to its design. By putting relevant technical disciplines together in teams, a way-of-working was developed that was both effective and efficient. An informal domain-specific language was created describing high-tech equipment; this language was transferred to new generations of design engineers by means of post-academic in-company training. This training was first available within Philips, and later became available at the universities and outside of Philips as well.

Although SE methodologies are being used, traditional SE as promoted by INCOSE (and as adopted in aerospace and automotive industries) has never been used in a formalised manner by Dutch high-tech companies. As an example, design process information, such as system requirements, has mostly been kept in office document and spreadsheet formats, not in formalised data systems. Formal reviews are conducted based on such documents, leading to quite some administrative overhead. Design decisions can be captured in presentation slides or just some email messages.

The sole source of truth as mentioned before is in fact a source distributed over many documents, of many distinct kinds, part of which are kept in document-based repositories. While these document-based repositories typically allow for some form of version control, other essential information management concepts such as traceability are often not supported. The system models on the other hand are kept in a variety of formats, specific to the model tooling being used. These models are sometimes maintained in the same version-controlled repository, but typically lack a managed co-evolution of the various models during the design of a system. There is no hard coupling of engineering information to the engineering process.

Dutch high-tech equipment design has been highly successful; our ability to design equipment that is among the most complex in the world is widely recognised. Still, we believe that we must evolve our SE methodologies to maintain our competitive edge and be able to design systems that are even more complex than the current ones. Our future SE must be tightly integrated with all engineering disciplines. Engineering design tools will become more interconnected. System requirements will not only be traced, but further formalised so they can be better analysed and serve as a basis to support automated synthesis of solutions. These developments can be captured under the term of model-driven (systems) engineering. Data science techniques (as well as AI techniques for design automation) will become important, not just to interpret the data generated in the equipment or to generate data to drive the equipment, but also to support the designer in the design of the equipment. In this case, the term digital engineering is being used.

Structuring the SE approach is becoming a more fundamental requirement for the engineering process. SE models should be organised (or in some cases developed) such that their dependencies and model relations are (semantically) meaningful; consider, for example, linking optical models to thermal or dynamic models. Defects in SE models will manifest as defects in the system being produced. This change will require a different approach and to achieve this, education of future systems engineers will have to adjust.

SE education

At universities of technology and universities of applied sciences, future engineers, including systems engineers, are trained. It is widely recognised in industry that SE roles require senior engineers with extensive domain and application knowledge, as well as experience in system design. We cannot expect engineers to pick up such roles fresh from university, so that leaves the interesting question on which aspects universities should focus their training for SE and systems thinking. In addition, we know that the receptivity for SE-related knowledge and know-how is not optimal for young students not having any industry experience. SE training in US and Canada is typically given as graduate training, after students have gained industrial experience as design engineers and after their bachelor training.

Where experience cannot be learned, we believe that the role of universities should be sought in laying a foundation on which future SE is based. By way of illustration, we mention some aspects that we think need attention in engineering programmes.

A more fundamental understanding of design processes and their fundamental aspects must be included in the programme. The coupling between ‘intention’ and ‘realisation’ is important to understand. Students must be able to deal with abstractions such as conceptual, functional, logical and physical reasoning in the context of a design objective. The difference between engineering models and scientific models is important for understanding the different objectives of modelling and design.

An important aspect that should be addressed in university is the understanding of connections and relations between various disciplines – technical disciplines such as software engineering and mechanical engineering, but also other disciplines that are relevant for design such as marketing and service engineering. The ability for productive multi-disciplinary collaboration critically depends on understanding of and respect for each other’s disciplines. Understanding the refinement processes and the corresponding languages of other disciplines is important as is the understanding of other design cultures that become relevant when working for external and/or international customers.

Proper identification and formalisation of requirements is an important skill for system engineers. These skills can be trained in university and will help the new engineers to become more effective in their job. Taking a systems perspective to derive requirements, determine their relative importance and their allocation in the requirements tree for the overarching system forces engineers to consider the objective of their task and stimulate them to start negotiations with other parts of the system their design will be part of more thoroughly.
Formalised optimisation of systems will become important given the increase in system complexity. For small parts of a system, an informal, qualified trade-off may be sufficient. For large and complex high-tech systems, these are too vulnerable to influences such as cognitive bias or incompleteness. Premature convergence to a single solution is sometimes difficult to avoid, the need for quantification may help prevent this. Currently, our system developments are typically based on budgeting for key parameters, and quantification trade-offs are easier when based on clear budgets.

Conclusions

Systems engineering for high-tech equipment is evolving into a critical engineering discipline due to the integration of ever more complexity, disciplines, dependencies and specialisations into the design process. There is a need for more comprehensive system overviews in the presence of high complexity, faster responses to changing requirements and boundary conditions, more formalised trade-offs considering many factors and more generally also a faster feedback cycle between all engineering disciplines and the SE coordination.

The role of universities needs to be adapted and intensified to establish a future-proof SE culture for high-tech systems. Unification of fundamental SE principles throughout the various educational programmes of the university will lay the foundation for consistency. A backbone of system design courses will provide a clear path towards required SE and design skills. Future systems engineers should be prepared for widening their view/scope of solutions and their impact (holistic applications, artificial intelligence, systems thinking). An active interaction with industry experience is a prerequisite to continuously tune the educational programme.

REFERENCES
[1] *www.incose.org/about-systems-engineering*
[2] *en.wikiversity.org/wiki/Systems_Thinking*