Applying Systems Engineering to Infrastructure Projects

Roger Farnham and Erik W. Aslaksen
Sinclair Knight Merz
Glasgow, UK and Sydney, Australia

1 Introduction

How to apply systems engineering and the benefits that arise from doing so is well known within the defence and aerospace industries, and requires no further elaboration here. Some other industries, in particular the chemical industry in its process design [1] and, more recently, the automotive industry, apply many of the same processes, but may not call them systems engineering. One area where the systems engineering methodology has not had a significant impact to date is in what might be collectively called commercial projects; the development, design, and construction of such infrastructure objects as motorways, railways, ports, power, industrial plant, mines, etc. From the nature of these projects and the engineering tasks that have to be performed, there does not seem to be any in-principle reason why systems engineering should not be equally beneficial in such projects. In this paper we first identify what we believe is the main barrier to applying systems engineering in commercial projects and illustrate this with a couple of case studies. We then describe and discuss a proposed approach to overcoming this barrier. However, implementing that approach has its own barriers, as is to be expected in an industry that is as traditional as the construction industry, and we therefore also look at some newer contracting schemes that might make the implementation easier.

2 The Problem

A central feature of the systems engineering methodology is its holistic approach to projects, both with regard to the breadth of issues and stakeholders involved, and with regard to the project life cycle, progressing in a top-down / bottom-up, seamless manner from “lust to dust”, with traceability throughout. Every issue and factor that has an influence on the total project outcome is considered from the very beginning, not as an afterthought later in the project when the most cost-effective handling of it may already have been precluded by preceding design decisions. This is accomplished by considering that complex of issues and factors, what Warfield [2] calls the “problematique”, as a system, and then developing the structure of this system in increasing detail as the project progresses, hence the characterization as “top-down” design.

However, in the commercial world, it is quite common to split a project into contractually separate segments; in particular, it is common to engage one consulting firm for the concept phase, and another one for taking the design forward to completion: construction, operation, and maintenance may all be separate contracts. This disjointedness causes problems with the application of systems engineering; each contractor sees its phase as “the project” and loses sight of what constitutes success for the project as a whole, and the benefits of a top-down approach are mostly lost.

This effect can be observed even within a part of a project, and a small example is afforded by the design-and-construct (D&C) phase of a recent project to build a major flour mill. The Owner went to the market with a Request for Tender (RFT) for the civil and structural compo-
nents, based largely on the milling equipment manufacturer’s drawings; Sinclair Knight Merz (SKM) was asked by one of the bidding construction contractors to quote a fixed price to them for the tender design. The only instruction from the contractor was to keep the tender design cost to a minimum, as not only was there the only the normal (less than one in three) probability of winning the job, but there was also some uncertainty as to whether the job would go ahead. A further request was to complete the design in three weeks. SKM submitted its quote and was subsequently engaged by the contractor to do the tender design, and submitted the tender design on time, together with a fixed price for completing the detailed design on the basis of this tender design. SKM was then not further involved until advised by the contractor until that the job had been won; SKM then completed the detailed design and construction. Unfortunately, throughout construction, and particularly towards and at the end, the contractor ran into a number of problems, both with the Owner regarding scope, and internally through a discrepancy between estimated construction cost and reality. The contractor then claimed that the SKM had not fulfilled its tender design obligations and that the information provided had been inadequate for estimating the construction costs.

This claim could not be sustained, however, it highlighted a serious weakness in this process, which would have been avoided if a systems engineering approach had been in place. Such an approach would have unfolded as follows. When SKM was asked for a quote for the tender design, we should have worked as a team with the contractor and asked: What do you need this tender design for? What is your objective? The answer would have been: A tender that will win us the job, while at the same time provide a high degree of assurance that we will have a satisfied client and make a reasonable profit. Then we should have analysed what information would be required to develop such a tender; what factors would be involved, what stakeholders would have to be considered, and what were the boundary conditions. In other words, we should have defined and understood the “problematique” for this little sub-project. It would then have become apparent that just delivering a tender design, as the contractor had asked for, was far from adequate for reaching the objective with any degree of assurance, and certainly not the most cost-effective approach. In particular, the level of detail provided by SKM should have been tailored to the level of knowledge within the contractor’s organisation.

The second case study we shall consider is one where a combined heat and power scheme is being put in place; however, the scheme is a variation to a contract for standard design power plant with the associated standard design documentation. The ‘customer’ for the heat is a process plant, which already has a heat source, which will be replaced by the hot water from the power plant. The process plant also has mature design documentation, but in a different system to that of the power plant. Also, the safety systems at the two plant are different, mainly due to the different risk present, with the process plant being deemed to be the higher risk plant, and having a higher level of safety management.

SKM are acting as owners engineer for the power plant developer, the Principal, and is project managing the interfaces within the overall system, particularly across the boundaries of the power plant, through a leased interconnecting corridor, and into the (already operational) process plant, as illustrated in Fig 1. The detail design is being developed by the power plant supplier, however, the differences in design documentation mean that this detail requires to be ‘translated’ into the (oil and gas) culture of the process plant, and similarly translations are required of the process plant requirements to the power plant systems. One area which has highlighted these differences, but has effectively initiated actions to address these design interface issues, is the running of system-wide HAZID and HAZOP [3] studies.

3 The Proposed Solution

To overcome these problems, there are two main avenues. One is to change the contracting strategy, and in this regard there are a couple of newer approaches that offer clear advantages of
a sequence of discrete, fixed price contracts. They all depend on some form of closer relationship between the Principal and the parties carrying out the work, and the first of these is an extended form of the Engineering-Procurement-Construction Management (EPCM) approach. The extension is that the Engineer is engaged already at the very inception of the project and takes responsibility for its development through all its phases, and thus is able to both provide continuity of the systems engineering processes and reap the benefits of the up-front definition and planning work.

The second approach is what goes under the name of “alliancing”; that is, where the Principal and the Contractor(s) form a team [4]. Not only is there a sharing of gain and pain, as well as a “best for project” culture that transcends the interests of individual participants, but the Principal provides the important continuity through the participation of his personnel in the team throughout the project, even if individual Contractors enter and exit the team along the way. In the second of the case studies above, in acting as the Principal’s (owners) engineer, SKM provides this continuity, and indeed has taken the role of ensuring that all parties are fully aware of the design, and that the most effective design decisions have been agreed by all the stakeholders. However, the collation of design documentation has been on an ad-hoc / when-identified-as-a-need basis.

Before outlining our proposed checklist, it is very important to realise that requirements fall into two very distinct groups: requirements on the project (the Work), and requirements on the system or object to be created (the Works). The former include requirements on treatment of staff, on maintaining insurance cover, on conforming to Environmental, Health and Safety (EHS) legislation, on reporting formats, on maintaining records, on liquidated damages, etc.; they are the requirements usually covered in the Conditions of Contract or a similar document. They are not the subject of this paper, as there is no requirement for continuity or traceability with regard to these requirements; they may differ considerably from one stage of the project to the next, and are, at least to a certain extent, a reflection of the risk allocation in each stage. Handling these requirements is more a task for project management than for systems engineering; our concern is solely with requirements on the system.

However, these contracting options are far from universally accepted, so recognising, at least for the time being, that a certain disjointedness with regard to contracts and participants is inevitable within commercial projects, we propose that each new contract stage within a project should start off with a stock-taking exercise. What is taken stock of, is the degree to which the systems engineering activities that should have been completed by that stage, have been completed. This would typically be a three-step process:

<table>
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<tr>
<th>Step 1</th>
<th>Make an inventory of all the documentation available (i.e. establish the project database). This might have been listed in the RFT; if not, it would normally be an initial activity anyway. This information is likely to come from a number of the stakeholders systems.</th>
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<td>Step 2</td>
<td>Analyse the documentation with regard to its adequacy as compared to what is required by the systems engineering processes, thereby determining what is missing.</td>
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<td>Step 3</td>
<td>Develop a plan for developing the missing documentation.</td>
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With regard to the first of these steps, we would like to suggest that there is, in most large infrastructure projects, whether green-field or brown-field, a process which displays much of the required information, and that is the hazard analysis process. As already mentioned, HAZID and/or HAZOP studies are conducted by representatives of the key end-users of the system, however, the EPC (the Contractor) and the developer (the Principal) will be there to ensure that
the safety management and operability deliverables are delivered at a reasonable cost. The key deliverable for the Systems Engineer is the review of operability.

A group of the process (‘system’) and control (also with a system perspective) engineers representing the designer(s) and the asset owners and operators come together to study the system using an agenda which has developed over the last 30 years. The agenda is a number of guide words testing how the design satisfies system safety, prompting discussion on how complete the design is. Prior to the start of the study, the chairman will have sent out a pack of information to summarise the design, generally for the benefit of operations staff attending, who may have only a high level understanding of the system to be studied. As the actual study proceeds, each sub-system is described in some detail by one of the design team. So a convenient summary of the design should have become available, prompted by the study taking place.

The main output of the study is a list of documented mitigations addressing identified hazards, and a list of actions to address hazards which are considered to require additional design of control measures. This output could be reviewed/interrogated to gain an understanding of the system, however, the output is basically a risk register to help complete the development of the system and then to manage its Operation & Maintenance during its operational life.

So, although the study provides the wrong output for the Systems Engineer, attendance at a HAZID or HAZOP, primarily as an observer, could provide an ideal opportunity to obtain the information required in the first step. The studies explore all system interfaces, generally by either following process fluid paths shown on Process Flow Diagrams (PFDs) in a HAZID, or using more detailed Piping and Instrumentation Diagrams (P&IDs) during a HAZOP, and references all the existing project documentation in the process of identifying existing controls or defining the development of further control measures. The study is often the first time all stakeholders have met together and a more complete system design review takes place. The system is broken down into a number of nodes; primarily to make the study manageable, however, the nodes are usually defined to be consistent with functionality.

It is for the second of the above three steps (Step 2) that we propose the use of a standardised template; initially for the start of detailed design as a separate stage, prior to letting a construction contract, but this could be easily modified to cover the start of a design sub-contract within a D&C contract, and other templates could be developed to cover other transitions. This would represent a “state of the project” determination from a systems engineering standpoint, and would allow the relevant systems engineering processes to be effectively applied.

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Our proposed checklist for the requirements on the system has the following structure:

I Requirements Definition

1.1 Is there documentation defining the stakeholders and their relationships to the project?
1.2 Is there documentation dedicated to defining the stakeholders’ requirements?
1.3 Are the requirements structured into groups of related requirements?
1.4 Have constraints (boundary conditions) and assumptions been included in the re-
   quirements definition documentation?
1.5 Is there an acknowledgement (sign-off) by the stakeholders that this is the complete
   set of requirements?
1.6 Have the consistency and the realize-ability of the requirements been verified?
1.7 Are there value functions associated with all of the soft requirements?
1.8 Are all the requirements measurable and verifiable, and has the method of verification
   of each requirement been specified?

2 Requirements Analysis

2.1 Is there documentation to show that the system functionality is derived from the
   stakeholders’ requirements?
2.2 Is there documentation to show that each of the stakeholders’ requirements is satisfied
   by the system requirements?
2.3 Is there documentation to show that each of the system requirements is necessary in
   order to satisfy the stakeholders’ requirements?

3 Change Control

3.1 Has a process been implemented to control any changes to the stakeholders’ require-
   ments?
3.2 Is there documentation to show that each change has been correctly reflected in the
   system requirements?

4 Requirements Management

4.1 Is the traceability, up and down, of the requirements development process (i.e. into
   levels of greater detail) adequately documented?
4.2 Have the current (latest) design documents (i.e. those that form the point of departure
   for the detailed design) been subjected to this requirements management process?

The answers to these questions may be a definitive “yes” or “no”; in many cases a sizeable pro-
portion will be somewhere in-between. The tasks may have been partially completed, or com-
pleted, but not documented in a form that is directly usable within the systems engineering
process. Furthermore, the relative importance of the questions is subjective and dependent on
the nature of the project. Nevertheless, despite these shortcomings, performing an audit based
on this checklist will give a good picture of the state of the project with regard to the effort re-
quired to implement a systems engineering approach at this point in the project.

4 Implementing the Solution

It is probably already apparent that introducing such a “state of the project” is not without prob-
lems. The first of these is, of course, that the audit itself represents “extra” work, and the cost of
carrying it out has to be covered somewhere in the project. In some (relatively rare) cases the
information required to carry out the audit (i.e. answer the questions in the checklist) is avail-
able already at the tender stage, and the tenderers could then perform the audit as part of the
 tendering process and include the findings in their proposals. However, because the success rate
is usually not better than 1-in-3, there is always significant pressure on keeping the tendering
costs to a minimum.

If the audit is not carried out as part of the tendering work, the tenderer could make a provision
for performing the audit and any resulting remedial work as part of his estimated cost. How-
ever, adding any such cost reduces the probability of winning the job, and would therefore generally not be acceptable.

The second problem is that any inadequacies identified by the audit may most likely lead to time-consuming arguments with the contractor of the previous stage, and even with the Principal, about what is “adequate”. In the absence of any systems engineering processes being defined within the contractual framework, it is very difficult to demonstrate the benefit of a particular process, and even more difficult to justify a particular level of effort. This justification is a major topic within systems engineering [5], and the situation is very similar to that encountered when introducing a quality system. Excellent engineering was performed long before any formal quality systems were introduced; the benefit of such systems arises through the assurance of a consistent level of quality, which can only be demonstrated over a large number of projects.

The third problem is that, even when there are no disagreements of any kind, the inadequacies would normally become apparent only after the start of the contract, and that only then is one able to start going about finding staff to develop the missing information. The resultant delay may not be acceptable; at this stage of the project all enabling hurdles, such as financing and approvals, have been cleared, and there is usually considerable pressure to progress rapidly to construction.

There is no simple and immediate solution to these problems, but it is clear in what direction the solution lies; it is quite similar to what took place when quality systems were introduced. The Owners or Principals, i.e. the organisations whose money is at risk, have to become convinced that a systems engineering approach is beneficial, and then incorporate the corresponding clauses into their contractual framework. Contractors did not adopt a quality system and conform to the ISO 9000-series of standards because they wanted to or saw it as beneficial; they did it because it was required by the contracts. At present, and within both Australia and the UK, there is little or no awareness of systems engineering among the owners and managers of commercial enterprises, and, with some exceptions, neither among government officials and the managers of government departments and enterprises. The systems engineering community has for too long been blinkered by its focus on the defence and aerospace sectors, where this situation is largely irrelevant; it is now important to put some effort into increasing the awareness of systems engineering in the commercial sector. INCOSE is trying to move in this direction through some of its working groups [6], and an early success story is the adoption of a systems engineering approach within the Dutch Ministry of Public Works [7], but there is still a change of mindset required, and the way that is reflected in the language we use [8].

5 Conclusion

We have identified some of the barriers to introducing a systems engineering approach to commercial projects, and proposed a way forward that would eliminate or reduce these barriers and allow most of the benefits to be realised. We illustrated both the barriers and the benefits by means of two case studies, and discussed what could be done to hasten the acceptance of systems engineering and an appreciation of its benefits by the commercial sector.

References


3. The HAZOP process was developed by the UK’s Imperial Chemical Industries (ICI) in the 1960s. In 1977, the Chemical Industries Association (CIA) produced a guide. This has now been superseded by the Institution of Chemical Engineers (IChemE) HAZOP Guide to Best Practice, 2nd edition 2008

4. Some background to the development of this contracting method is contained in *A resource and research bibliography*, available online at www.memullan.net/ecti/Alliance_Contracting.htm, and a manual is available at www.dtf.vic.gov.au/projectalliancing.


6. Two Working Groups are particularly relevant, the Infrastructure WG, chair Alain Kouassi, alain.kouassi@incose.org, and the Intelligent Transport and Transit WG, co-chairs Michael Krueger and Anne O’Neill, ittswg-info@incose.org.

7. The manual is available online at www.leidraadse.nl.


Figure 1 - CHP case study