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DESIGNING COMPLEX SOCIO-TECHNICAL SYSTEMS – EXPERIENCES WITH STUDENT PROJECTS ON INTEGRATING TECHNICAL, INSTITUTIONAL AND DECISION PROCESS DESIGN

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1. Introduction

Designing large-scale, complex, technology-enabled systems, such as industrial clusters, inter organizational information systems, energy systems, or logistic systems, is a complex task in many respects. It involves deciding on a great number of interrelated design variables, often using state-of-the art technology, to create a feasible well-performing system that fits well into its future environment. Deciding on these design variables involves, in addition, a great number of stakeholders such as a commissioner, designers, clients, operators, builders and residents, with possibly diverging interests. In the faculty of Technology, Policy and Management of the Delft University of Technology, we aim to develop a body of knowledge that enables engineers and policy makers to deal with the design of these types of complex socio-technical systems in a better way [Bots, 2005]. This paper addresses the evaluation of a relatively new capstone project in which students are asked to apply the acquired knowledge on designing complex socio-technical systems. The central issue in the evaluation is whether the project in its present setup is an adequate form for achieving the learning objectives of the course.

We transfer this knowledge to students in the faculty's Bachelor and Master programmes, but in particular in the Systems Engineering Policy Analysis and Management (SEPAM) Bachelor and Master of Science programmes. In these programmes we educate multi-disciplinary engineers that are able to bridge the gap between the technical arena's, in which mono-disciplinary engineers operate, and the social and political arena's, in which policy makers and managers operate. SEPAM students are, therefore, educated in a multidisciplinary environment, their curriculum providing a solid background in applied mathematics, systems engineering, policy analysis, organization and management, combined with essential knowledge of a selected technological application domain as well as the associated legislation, economics and public management in that domain. The technological application domains students can choose from are a) Transport, Infrastructure and Logistics, b) Energy, Water and Industry, and c) Information and Communication Technology. The objectives of the interdisciplinary curriculum for SEPAM students are [Weijnen et al, 2001]:

- ability to deal with a variety of complexities, including multiple stakeholders, uncertainty and multidisciplinarity;
- versatility in both systems and policy analysis, design and implementation;
- knowledge of systemic tools and techniques and their usage;
- substantive knowledge of the chosen application domain.

The complete programme (BSc and MSc) takes 5 years to complete and is concluded with a Master's thesis. During the three-year Bachelor programme, methods and techniques and basic knowledge are provided aimed at *analyzing* complex socio-technical systems in general and in particular on the domain chosen. For the two-year Master programme the focus shifts towards *design*, intervention and management of complex socio-technical systems. Basic courses that are taught to students from all domains are, amongst others, organization and management (public and private), mathematical modelling including continuous and discrete simulation modelling, quantitative and qualitative research methods and data processing, multi-objective and multi-actor analysis of complex problems, economy, law and policy (public and private), and design and management of policy and decision making processes.

In the SEPAM BSc and MSc programme, theories, concepts, methods and techniques are taught in theory modules. The practical work within these courses is aimed at understanding and applying the concepts, methods and techniques separately in straightforward situations. The ultimate aim of the programme is that students are able to use the concepts and methods conveyed in the theory modules in more complex real life situations. For this purpose the programme offers project modules, as this work form is particularly suitable for learning how to apply acquired knowledge [Raucent e.a., 2005; Powell and Weenk, 2003]. The capstone project for the MSc programme is the "SEPAM design project" into which students can enroll after they passed the larger part of the theory modules. The design project has now been taught for two consecutive years, so this is a good time to reflect on its learning objectives and outcomes.

2. The SEPAM design project and its objectives

The SEPAM design project involves a design assignment in which students apply the acquired theoretical knowledge on design and management methods, tools and principles for systems, infrastructures and services to a realistic case in their domain. According to the course objectives, on completion of this course students will be able:

- to choose suitable system design methods and tools, taking into account the substantive and process characteristics of the system and the multi-actor environment
- to apply the chosen design methods and tools for this case;
- to design a system taking into account technical, institutional and decision-making aspects relevant for this case.

In total about 60 students took part in the course, about 20 students in 2004 and about 40 students in 2005. The project teams (17 teams in total) consisted of 3-5 students from the same specialisation domain. With students of the same technological application domain in a team, it is possible to achieve sufficient depth and technical rigor in the technical design.The design assignments for the three domains were the same in both years:

- for the Transport, Infrastructure and Logistics domain: make a (re-)design of a rail tunnel through the centre of the city of Delft;
- for the Energy, Industry and Water domain: design a city heating system using industrial residual heat for the city of Delft;
- for the Information and Communication Technology domain: design a system for roadpricing for the Netherlands.

Students were asked to design a complex multi-actor system related to their domain applying the specific SEPAM perspective on designing. This implies that they needed to consider in a balanced way three main perspectives:

- the technical perspective, that focuses on the physical artefact and its components, and on functional and technical system requirements, technological design choices, possibilities and limitations, resulting in a technologically feasible, robust, valid technical systems design. The knowledge applied orginates primarily from courses on systems engineering in general and specifically on the domain.
- the institutional perspective that focuses on the organizational arrangements between the actors that will be involved in the design, implementation and operational phase of the system. This results in an institutional design that deals with division of tasks, responsibilities, costs,

benefits and risks. The knowledge to be applied here are theories and approaches in the field of institutional design, new institutional economics, evolutionary economics, and various regulation theories [De Jong et al, 2002; Ostrom, 1990].

- the decision-making (or 'process' in our jargon) perspective, that focuses on how the systems and institutional design can be realized in a dynamic multi-actor setting. Process design and management principles should be applied in such a complex, multi-actor decision making context. The resulting decision process design deals with how stakeholders are involved, under which conditions, on which topics and which steps need to be taken. The knowledge applied here is a combination of systems engineering, e.g. [Maier & Rechtin,2002; Dym & Little, 2004] and theory on process design and management [Bruin, Heuvelhof and In 't Veld, 2002].

The three resulting designs cannot be developed in isolation, they interact and are strongly interrelated: specific technological choices affects which actors are involved and thus the options for institutional and process designs. The other way around, preferences with regard to institutional arrangements affects options in the technical design. This implies that the technical sphere, although dominant, does not necessarily dictate the system design process. Moreover, the systems'environment which is a static constraint in many other technical design disciplines such as civil engineering or mechanical engineering, is brought into the design space for our students. Both the design process and the institutional arrangements need to be considered and designed to fulfil the overall system requirements.

The challenge for students is vast. In the SEPAM-programme, we provide the students with concepts, methods and techniques to deal with the design on three main perspectives: technical, institutional and decision-making. There is, however, no off-the-shelf handbook for designing socio-technical, complex systems, that explains how to link the technical, institutional and decision-making aspect. After two years of teaching the course we find it important to look into the way students deal with this challenge in more detail. We have evaluated the following issues:

1. How did the students deal with the synthesis of the three perspectives in making the system design?
2. What were the major difficulties that students were confronted with in making the designs?
3. How do students perceive the project? Do they feel the learning objectives are met? What knowledge did they find necessary?

For a detailed analysis of the student work (issue 1) we have limited ourselves in the context of this paper to the case of the Energy, Industry and Water domain which is discussed in the next section. For researching issues 2 and 3 we have issued an anonymous questionnaire among the students, and the results are discussed in section 4.

3. City heating using residual industrial heat

The city of Delft has formulated a Climate Plan based on the environmental goals set in the Kyoto Protocol. The biggest project included in the Delft Climate Plan is the use of residual heat from a chemical plant for heating parts of the city of Delft. Designing and implementing such a system is extremely complex due to the different types of factors involved, and was therefore chosen as a case for the students who specialize in Energy, Water and Industry.

Students were asked to design the technical system, including pipes, pumps, capacities, network topology; the design/decision process, addressing questions like who?, when?, how? and what? and the institutional arrangements, addressing rules, laws, responsibilities and combination with CO_2 emission trading. The students were confronted with many actors in the surroundings of the design, who would somehow influence the realisation of the design and its implementation. Examples are the citizens of Delft, private companies, developers of industrial/commercial areas, existing housing companies, and new housing areas. Questions would have to be addressed concerning tariffs, consumer choice, regulatory constraints, and financing issues. The deliverables required at the end of the project are:

- *for the technical design:* a block diagram and a flowsheet, a mass balance, an energy balance, sizing calculations of most important equipment, cost estimates (investment and operation), technical restrictions to dwellings and buildings. A typical system architecture that would result from these design projects is shown in Figure 1.

- *for the institutional design:* design for the operational institutions, financial structures, regulatory constraints, ownership, overall cost and benefit analysis, and comparison to other energy saving possibilities.
- *for the process design:* a process design for the system design process involving real stakeholders in future years, including negotiation rules and negotiation rounds.

Four groups have taken up this design project in the past two years, and they all managed to deliver a final integrated design. Depending on the interests of the students, the focus of the designs was different. Some groups focused on a thorough technical design with proper heat and mass balances, reliability calculations and detailed cost estimates. Other groups focuses more on the institutional arrangements and kept the effort to the technical system design as low as possible. In Table 1 we summarize and compare the outcomes of four projects. The Table is not exhaustive with respect to the products and outcomes, but serves as an illustration of the main similarities and differences.

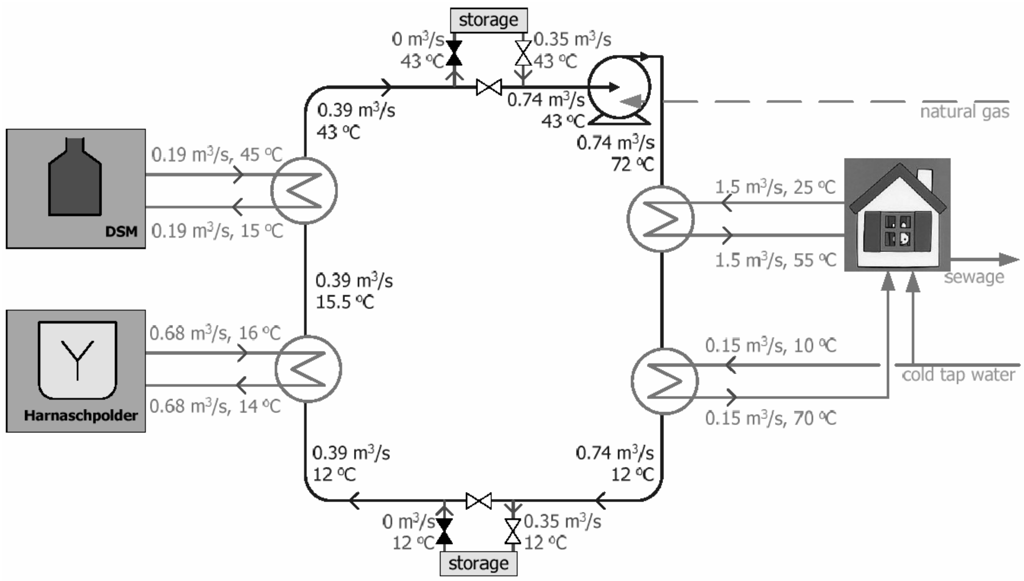

Figure 1. Typical block diagram of a resulting technical design

The results in Table 1 show a very diverse picture of the realized designs. Although it is characteristic for design projects that no two design teams produce the same results, the variety in results for these four design teams is significant. They differ in design approach (many choose the technical design as the leading perspective) and design outcomes. We also see that the institutional and process design are different for each technical design, which was to be expected. Group 2 took a fully integrated approach and designed all three aspects of the complex system in parallel, whereas others treated the institutional and process design as a 'add-ons' onto the technical design. Overall we saw that students who took an integrative approach tot the complex systems deisgn had a better notion of the interactions between the subsystems. In fact, the above average students were able to grasp the fully integrated concept, leading to vialble and realistic designs. Other students, who approached the design as a decoupled systems of three subdesigns, would focus on the traditional technical design, and would find that in designing the institutional subsystems thay had to iterate to their technical design and rework it.

Table 1. Comparison of project outcomes for the city heating system

	Group 1	Group 2	Group 3	Group 4
Leading design perspective	Technical design	Process design	Technical design	Technical design
Integration of T,I, P aspects	disconnected	fully integrated	integrated	connected
Technical				
Number of sources	1	2	1	1
Number of sinks (areas connected)	4	6	4	6
Network Concept	centralized and decentralized	centralized with backup	centralized with backup	centralized
M & E balances	available	detailed with pinch analysis	available	very detailed
Distribution network: Pipe diameter Pipe length	0.5 and 0.1 m 8 and 80 km	n.a. 5.9 km	n.a.	0.48 and 0.28 n.a.
Investment Cost	27.8 M€	21.4 M€	9.5 M€	10.4 M€
Operational Cost	2.0 M€ / yr	n.a.	0.4 M€	n.a.
Institutional				
Financing / Ownership	Public Private Partnership	PPP: Design Build Maintain	PPP	PPP: Design Build Finance Operate
Process				
Implementation process	3 negotiation rounds	8 rounds	7 phases	public tender process

4. Survey

In the survey we have focused on the difficulties students encountered in making the designs and their perception of the course (issues 2 & 3 in sections 2). We have sent questionnaires to personal e-mail accounts of students that participated in the project in 2004 (21 students) and 2005 (38 students). Participation to the survey was anonymus and voluntary, and most of the students addressed had already received a grade. 22 questionnaires have been returned, with a response of 36% for each year. A number of statements was presented to the respondents and we asked them to assess their level of agreement on a 5-point scale (1= totally disagree to 5 = totally agree). In formulating the statements, we aimed to cover various issues related to the effectivenss of this project:

- Some general statements concerning perceived relevance, expectations and choice of the case that can affect student motivation (S1 to S4)
- Some statements to assess whether the knowledge we expected them to apply was indeed required according to students (S11 tot S14)
- Some statements to assess wether students found that learning objectives have been met (S15 to S22)

In addition we formulated some statements that address issues supervisors brought up in evaluation of student work, i.e., deciding on the desired level of detail in formulating the design and pinpointing critical components in the design (S5 to S10). The resulting set of statements and the survey outcomes are presented in Table 2.

Table 2. Overview of survey results

Statement (S)	Average (n=22)	Standard deviation
General statements		
1. The project is relevant for the SEPAM programme	4.5	0.51
2. The project was challenging	3.8	1.14
3. The design case for my domain was interesting	3.6	1.22
4. The project has on the whole fulfilled my expectations	3.2	1.15
5. Decisions on the level of detail of the technical design were important	4.0	0.72
6. Decisions on the level of detail of the institutional design were important	3.5	1.06
7. Decisions on the level of detail of the process design were important	3.3	1.39
8. It was difficult to pinpoint the critical technical components or aspects	2.5	0.91
9. It was difficult to pinpoint the critical institutional components or aspects	3.4	0.9
10. It was difficult to pinpoint the critical decision-making components or aspects	2.9	1.02
Statements on knowledge needed		
11. The project team needed knowledge on institutions and institutional design	4.3	0.77
12. The project team needed knowledge on the design and management of decision-making processes	4.0	0.72
13. The project team needed knowledge on desigining systems and systems engineering in general	3.9	0.77
14. The project team needed knowledge on systems and desigining systems on my technical domain	3.7	0.83
Statements on the learning objectives		
15. I have learned to deal with a design situation with many degrees of freedom and various sometimes contradicting sources of information	3.7	0.83
16. I have learned to choose suitable design methods and/or techniques.	3.3	0.94
17. I have learned to apply design methods and techniques in this case	3.7	0.84
18. I have learned to make a (good) technical architecture for the design case	3.2	1.05
19. I have learned to make a (good) institutional design for the design case	3.2	1.18
20. I have learned to make a (good) process design for the design case	3.5	1.06
21. After the project, I understood better where the work of the systems architect starts and where that of the designer/constructor starts	3.0	0.84
22. After the project, I understood better how design decisions in the technical design, in the institutional design and in the process design influence each other.	3.6	0.91

The project is generally perceived as being (very) relevant for the SEPAM Master programme (S1). On average it is seen as challenging, but opinions vary more here (S2). The perceived level of interest for the three design cases has a similar average and variance (S3). We expect, but did not determine, a correlation between the level of interest with the domains.With regard to expectations (S4) we conclude that the project performs neutrally: the course delivers what students expect.

The statements on the level of detail (S5 to S7) in the designs originates from a concern that is often a topic of discussion in talks with supervisors. The highest score is for the technical aspect, which seems to fit the observation made during supervision. Students find it difficult to determine the required level of detail of the system or of system components for a good technical design on an architectural level. For the institutional design and the process design this issues is only slightly less relevant. The outcome of these statements seem to correspond with the outcome of the statement on the boundary between the work of the systems architect and that of constructeur (S21). Typically, this outcome signals that this is a topic we need to pay even more attention to in the courses preceeding the project.

The results on the statements on determining the critical components or aspects (S9 to S11) seem to contradict observations made by some supervisors. Students perceive this not as a very difficult task, whereas supervisors conclude after looking into various reports that many project teams come up with different critical components or aspects for the same design cases.It is possible that students are unaware that they did not perform up to our expectations in this respect. The complexity of the cases, leaves ample possibilities for the students to come up with various sets of critical components and aspects. We, as teachers, ideally would like them to show that they have an overview of all critical issues in the design and that, from there, they decide to limit their project to a specific set based on some sound argument for the choices they made. It is possible that misconceptions on the nature of design activities is an axplanatory factor for this difference between student perceptions and supervisors' observations This requires our attention as such misconceptions can inhibit an effective learning process [Newstetter, 2001]. In addititon, we will need to clarify our expectations better in the assignment and in our feedback to students.

Students find on the whole that the knowledge fields we would like student to apply in the project are indeed all needed (S11 to S14). Althought the differences are not really significant, the need for technical knowledge design is perceived on average as less necessary than knowledge on institutional design and the design of decision processes. The reasons for this cannot be extracted from this survey. A possible explanation can be that the theory to be applied for the latter to disciplines can be drawn back to two particalur courses, whereas the systems and technical knowledge to be applied originates from various previous courses. Another explanation could be that the perceived difficulty of the three types of designs influences their answers.

The most positive results (average over 3,5 and variance below 1,0) with respect to the statements on the learning objectives (S15 to S21) are the ones related to dealing with complex real life design situations and the application of methods and techniques, and understanding how the technical, institutional and process design influence eachother (S15, S17 and S22). This is an important result for us as these are the main learning objectives of the project. With respect to learning how to make a specific design, albeit technical, institutional or process design (S18 to S20) we see a large variation in the answers. We expect that this is due to the tasks divisions made within the project teams, where the work on the three partial designs are divided among the group members.

5. Conclusions

The MSc programme on Systems Engineering, Policy Analysis and Management culminates in a capstone design project in which students successfully design a real life complex system, concerning technical, institutional and process decision making aspects.

The analysis of the project outcomes for the city heating case conveyed that, although students are able to finalize a feasible design in the time available, the results span a wide array of outcomes. The myriad of solutions for the decision-making process design reveals that we should teach students to better identify the critical design issues for complex design problems like this. The survey results confirmed our idea that the project sucessfully serves as a capstone project, integrating the knowledge gained in the preceding theory modules. The survey also showed that students saw the need for an integrated approach to obtain the final design, and that the institutional and decision making process knowledge was considered to be very crucial.

The evaluation of the design project, of which the outcomes are sketched in this paper, provides us with guidelines for further improvement of the capstone design project. Among other things we will provide students with more methods, frameworks or guidelines on how to combine and relate the three design perspectives. In addition to many multi-disciplinary courses already in the programme, we will teach about multi-disciplinary design projects in more detail in order to prepare the students for the complex design task at hand in this capstone design project.

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