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Designing socio-technical systems: Structures and processes

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Abstract. *The Systems Engineering, Policy Analysis and Management (SEPAM) MSc curriculum taught at Delft University of Technology focuses on the design of socio-technical systems (STS). We teach our students to structure design activities by considering what we call the TIP aspects: Technical systems, Institutions, and decision-making Processes. Students find TIP design difficult, not only because STS design is complex (this difficulty can be overcome with time and practice), but also because the I and P concepts seem difficult to grasp. Our students struggle with the notion of institution, the lack of a general framework for institutional design, and the fluidity and ambiguity of the concept of a decision-making process in the context of STS design. The objective of this paper is to clarify the TIP elements and to refine the TIP way of thinking. In clarifying the elements, we make a distinction between structure and process. Our premise is that an engineered artifact is a structure that, together with the context in which it is implemented, produces a process that performs the intended function. Our distinction between structure and process shows why the acronym TIP design is somewhat misleading. The T and I refer to structures, while the P refers to processes. This paper adds to the TIP design way of thinking by showing the analogies between technical and institutional structures. We argue that systems thinking/systems design applies to any artifact, be it technical or institutional. The structure-process distinction also allows us to better understand the system life cycle and clarify the concept of a decision-making process. Decision-making processes are important processes in all phases of a system life cycle, and they are themselves shaped by institutional structures which are placed in a context.*

Keywords. *Systems design, systems engineering, structures in systems engineering, processes in systems engineering, decision making process, institutional design.*

1 Introduction

At the faculty of Technology, Policy and Management (TPM) of Delft University of Technology, we teach students about the design of large-scale socio-technical systems (STS), in particular infrastructures that provide transport, energy, or telecommunication services. Such large-scale socio-technical systems cannot be designed – they develop – and yet they harbor a variety of design activities. In our teaching we exercise a way of thinking about these STS-related design activities that we call "TIP design".

TIP design means that the design takes into account *T*echnical, *I*nstitutional and decision *P*rocess aspects. Socio-technical systems design requires inter-related design of a technical system, a set of institutions (i.e., rules that constrain human behavior), and decision-making processes (Bots, 2007). The TIP perspective helps to structure the design activities related to STS. However, given the complexity of STS it is not surprising that students find TIP design difficult to grasp. We attribute this difficulty for one part to the intricate, multi-level, nested nature of T and I aspects of STS, which makes them intrinsically hard to comprehend. The problem with the P aspect, however, seems not so much due to the complexity of the socio-technical system, but rather to the fluidity and ambiguity of the concept of *process*. Where technical components and institutional rules can be understood as static "things" that have been engineered for a purpose, processes are dynamic flows of events, of changes that "happen". The P aspect is ambiguous because several decision-making processes are relevant when reasoning about TIP design: STS engineers have to consider simultaneously the decision-making processes related to different STS life cycle phases.

With this paper we aim demonstrate that TIP design actually means designing T and I components that produce *functional processes*, of which decision-making processes (P) are but a subset. We will argue that this insight will help students to disentangle a complex STS, recognize functional processes, and design functional components. We start with clarifying the relation between T, I and P. While doing so, we will show that T and I components are artifacts that can be designed, while processes are the result of placing artifacts in their context. A key insight we seek to transmit is the analogy between the functioning of a technical artifact and the functioning of an institutional artifact: institutional artifacts relate to human behavioral processes in much the same way as physical artifacts relate to physical processes. We expect that this will bring more clarity and rigor to the TIP approach, and in this way make it easier for students to understand and conduct STS design activities.

In Section 2 of this paper, we explain the difference between structure and process, and make a further distinction between T and I structures. Although the "building blocks" of T and I structures are different, we argue that a systems engineering approach can be used to design and implement both types of structure. In Section 3 we analyze STS design by distinguishing life cycle phases as processes. These processes comprise both physical and institutional processes, with different artifacts structuring these processes. Decision-making processes are conceptualized as institutional processes that can be part of all phases of the system life cycle. In Section 4 we zoom in on the process of design. The process of design is described as a decision making process for which an institutional structure can be designed that can produce the design process. In the concluding Section 5, we suggest ways for refining the TIP-approach.

2 Structures shape processes

To clarify the relation between T, I and P, we introduce a very general conceptual model of design that will allow us to think of these aspects of STS in a systematic, design-oriented way. The main proposition that underlies this conceptual model may be summarized as $A + C \rightarrow P$, which is shorthand for "any engineered artifact A is a *structure* that, together with the *context* C in which it is implemented, produces a *process* P that performs the intended function of A". The second proposition is that engineered artifacts consist of technical structures (being a subset of physical/material structures) and institutional structures (being a subset of social/psychological structures). The third proposition is that technical structures shape[1] physical processes, while institutional structures shape decision-making processes. To illustrate the meaning of these concepts, we will present some examples taken from the case we use in our present systems engineering course. To make these examples more effective, we briefly introduce the socio-technical system that is central to this case.

Case: Electronic ticketing system for public transport in The Netherlands.
In 2000, a new law on public transport was passed in The Netherlands, aimed at making public transport more efficient and more client-oriented. To comply with the new law, the Dutch government opted for the introduction of a national electronic ticketing system for public transport services (PTS). This complex socio-technical system should perform at least these main functions:

1. *Enable private companies to offer PTS, i.e., create and maintain a repertoire of PTS by adding, modifying, or deleting specific PTS, and defining the associated fare and conditions;*
2. *Enable people to purchase PTS using common modes of payment;*
3. *Control access to PTS so as to ensure that transport services are used only by travelers who have purchased the right to do so;*
4. *Provide traveller behavior information that allows operators to view/analyze data on the use of the services they offer;*
5. *Act as a clearing house, i.e., ensure that operators receive their proper share of fares collected for transport services;*

To these main functions one could add providing after sales service (e.g., reimbursement) and sanctioning (e.g., fine administration), but these functions could also be seen as part of functions 2 and 3. Note that the electronic ticketing system is a subsystem of a larger sociotechnical system that also includes the actual service provision process (transporting people from A to B) and the technical infrastructures and associated institutional structures that are needed for this process.

To illustrate how the notion that an artifact, when placed in a context, produces a process ($A + C \rightarrow P$) applies to the electronic ticketing system, we first consider a process that is related directly to the access control function. This function is effectively performed when only people who have purchased a PTS can make use of

[1] Please note that we write "structure *shapes* a process", rather than "*produces*", to emphasize that a structure alone (i.e., without context) will not produce a process.

this service. Since public transport is a physical process (it moves a person's body from one place to another by means of some multi-person vehicle), accessing a PTS is a physical process as well (e.g., entering a vehicle, usually via a platform). This means that access control can be realized by means of physical barriers, such as a gate that opens only when a valid "proof of purchase" is presented. Note that the gate artifact will produce the accessing process only in a context that satisfies these conditions: (1) there are travelers who wish to pass (so the PTS provided on the other side must be in demand), and (2) the gate is the only access point (or travelers will go around it).

The accessing process would typically comprise these sub-processes: reading the presented "proof of purchase", checking its validity, and opening the barrier. Each of these sub-processes is shaped by a component of the access control artifact, for example: an RF communication device that can read data from a contactless smart card, an information processing device that can verify whether the PTS provided at the platform has indeed been purchased, and swing gates that will allow (or not) a single person to pass. All of these components are themselves artifacts, which in turn comprise component artifacts.

This example illustrates several important things. Firstly, for an artifact to perform its function, its context must feature (1) structures in which the artifact can be "embedded", and (2) a "drive" that generates the flow of events (= the process). A gate will not perform its access control function unless it is part of a larger structure comprising the platform to which it provides access, and a fixed barrier that prohibits access other than through the gate. And, equally important, the process of travelers accessing a train platform only occurs when there are people who wish to travel. Likewise, the microchip on a contactless smart card is part of a larger structure comprising an antenna and a sandwich of resilient plastic cards, while the electronic processes that make the card function are driven by the magnetic waves transmitted by a nearby RF communication device.

Let us now consider the function to act as clearing house. This function is effectively performed when transport operators receive their proper share of the fares that are collected for transport services. Similar to the access control process, the clearing house process comprises several sub-processes: establishing the total revenue from collected fares, establishing the relative operator shares, and transferring the money to the respective operators' bank accounts. These sub-processes may be shaped by different components of the clearing house artifact. Provided that the artifact that shapes the purchasing process performs adequate record keeping, the total amount to be distributed can be obtained by means of a query on its data base. What is the proper share for each operator will be defined by a formal agreement among the operators. Such an agreement could, for example, be that each operator O receives the total amount that travelers have paid while purchasing PTS offered by operator O, but many other fare distribution schemes are conceivable. The money transfer can be effectuated by means of payment orders to a bank. Note that all of these components are forms of information processing devices[2] that, when decomposed further, will comprise material components only at the level of information carriers (e.g., paper and ink, disks).

Distributing the fare revenues is in essence an immaterial process guided by an institutional[3] structure: the formal agreement among operators. This artifact can function only because it is embedded in a context featuring other institutional structures (notably money and civil law) and associated socio-technical artifacts such as banks and law courts. The main "drive" that generates the clearing house process is the desire of the operators to make a profit.[4]

Our examples show that indeed A + C → P. In each example, the artifact that is designed is a structure (a system composed of static components) that, when implemented in a context, produces a process (a dynamic "flow" of events), and it is always this process that meets the client's needs, not the artifact as such. The examples also show that in a complex artifact such as the electronic ticketing system, the duality of structure and process can be observed at many different levels, and that processes can be seen to occur sequentially (e.g., scan – verify – open gate) as well as simultaneously (e.g., the electronic processes on the card and those in the RF communication device). Nested processes generally are shaped by nested structures, and concurrent processes generally require parallel structures. Finally, the examples illustrate two distinctions that we find useful to make in the context of systems engineering: (1) between physical/material structures and social/psychological structures, and (2) between natural structures and artificial structures (see Fig. 1). Artificial structures (= technical artifacts + institutional artifacts) can be designed; natural structures will always be part of the context. We purposefully do not apply this typology to processes, because processes are always shaped by an artifact and its context.

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[2] Computer programs are essentially institutional structures, as they code rules. The SQL statement SELECT Operator.Name, Operator.BankAccountInfo, SUM(SoldTransportService.PurchasePrice) AS Amount FROM Operator INNER JOIN SoldTransportService ON Operator.OperatorID = SoldTransportService.OperatorID WHERE (PurchaseDate >= "05/12/2011 00:00") AND (PurchaseDate < "12/12/2011 00:00") GROUP BY Operator.Name is an artifact that, when placed in the proper context (a database with the mentioned tables and fields), will produce a computational process that performs about half of the clearing house function. The resulting table will serve as a component of the institutional structure that can co-produce (with a bank) the money transfer sub-process.

[3] Note that we assume here that this agreement was purposefully designed, and hence an artificial structure (see Fig. 1)

[4] Additionally, we could mention time as a driver if the contract specifies, for example, that the revenues are to be calculated over weekly periods (Monday through Sunday), and that the due amounts are to be transferred no later than 48 hours after a period ends.

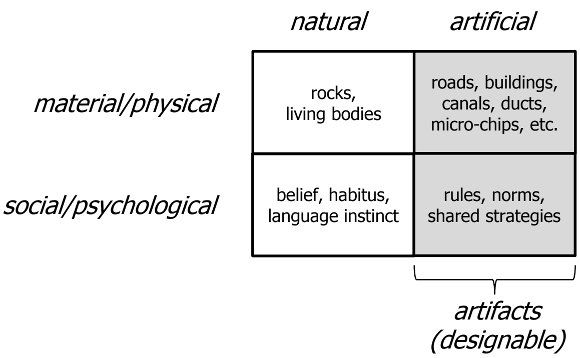

Fig. 1. A typology of structures.

Artificial structures are also referred to as "human-made systems" (Blanchard and Fabrycky, 1998, p. 4). When we consider the "building blocks" from which these structures are made, it seems evident that the building blocks for technical structures will always be some form of physical matter. Being immaterial, the building blocks for institutional structures are less evident. Crawford and Ostrom (1995) argue that the building blocks of institutional structures are "rules", "norms" and "shared strategies", and that these can be defined using a simple grammar: ADICO[5].

Artifacts (technical and institutional) can be designed. By "designing" we mean that system engineers can conceive these structures "on paper" and assess (e.g., by means of reasoned argument, or through simulation studies) how effective they will be, given a specific context, in shaping the processes so as to perform the intended functions. This assessment prior to actually realizing the structure in its context is a key characteristic of design: it distinguishes "designing" an artifact from "developing" an artifact. By "a design" we mean the representation of the structure "on paper". A design typically guides "implementation", that is, the act of realizing the structure within its context.

Implementation (e.g., installing swing gates in the access points to a platform, or communicating safety instructions to passengers) is also a process. More interestingly, implementation processes are shaped by artifacts: notably designs (e.g., technical drawings) and other institutional artifacts (contracts, project schedules), but

[5] The ADICO grammar entails that every rule specifies the attributes (A) that define the group to which the rule applies, a deontic (D) that defines for some action or aim (I) whether the rule permits (D = "may"), prohibits (D = "may not") or obliges ("D = "must") this action, the condition (C) that states where and when the rule applies, and the "or else" (O) that states what sanctions members of the group may incur when they disregard the rule. An example of a rule would be: "All people aboard a train must present a valid ticket when so asked by the conductor, or else they incur a fine of 100 euro". A norm is a rule without an explicit sanction (i.e., no O part), for example: "People travelling in a compartment may use their mobile phone only when no other person in the compartment objects". A shared strategy also lacks the deontic: "People wishing to play bridge while travelling take seats in a compartment that features a table".

often also technical artifacts (e.g., scaffolding, molds for casting concrete). These artifacts are "transient" structures in the sense that they shape a temporary process that produces a new structure, after which the transient structure is obsolete.

Being transient, these structures are easily forgotten in discussions on design. In our example of the clearing house process, we focused on the formal agreement that structures this process, ignoring the process of negotiations that eventually produced it. This negotiation process will also have been shaped by more or less transient institutional structures: invitations, meeting agendas, and, more in general, social conventions for "doing business".

Institutional structures are special in that they may be "self-referencing" in the sense that they shape processes that change their form. Business contracts, covenants, and other formal agreements commonly contain clauses specifying procedural rules that define how the agreement may be changed. In other words, the agreement artifact comprises institutional structures that in certain contexts will produce a process that effectuates the artifact's own structure

3 Processes in systems engineering

In terms of the previous section, systems engineering entails the production of an artifact A ("the system") that performs its function by shaping a process within its context ("the environment of the system"). If we apply our conceptual model to systems engineering, the life cycle of artifact A can be considered to comprise the processes shown in Fig. 2. The outputs of these processes are structures which, in an appropriate context, will shape the next process. The process of designing artifact A will produce a design D(A), which is an institutional artifact. When this artifact D(A) is then placed into a context of capable people and adequate resources, it will shape the implementation process of A. This implementation process realizes the artifact A within its designated context, where it shapes its process of operation.

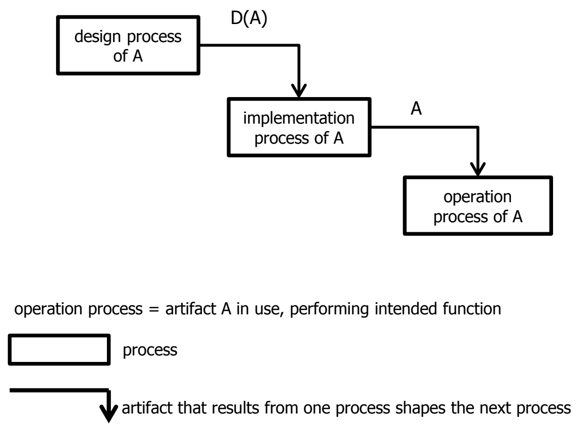

Fig. 2. Life cycle of processes related to system A.

Intuitively, one would say that the operation process of A should be the focus of any systems engineering activity, since it is this process that performs the intended function of A. The SE literature, however, emphasizes that the core of the systems engineering discipline is that structures be defined explicitly for *all* processes. This will be further discussed in Section 4.

Distinguishing different life cycle processes improves requirements analysis
System A is designed to perform its required function. The functional requirements of the system will be related to the system in operation, because by its operation the system serves the client's need. In the example of the electronic ticketing system, the combined technical and institutional structures that constitute the ticketing system (A) will, when put into context, perform the intended access and payment functions.

The operation process of A is the system's functional process. Implementation, maintenance, and decommissioning of A are also processes. Given the function of artifact A (e.g., controlling access to a platform), maintenance and decommissioning this artifact are non-functional processes. Maintenance and decommissioning processes are to some extent shaped by A, and also (and more so) by other artifacts, such as maintenance instructions and schedules. Because A will shape not only its functional process but also related non-functional processes, engineers should consider these processes when designing structure A.

We can generalize this by stating that the requirements that are taken into account during the design process should consider the processes following the design (see Fig. 3).

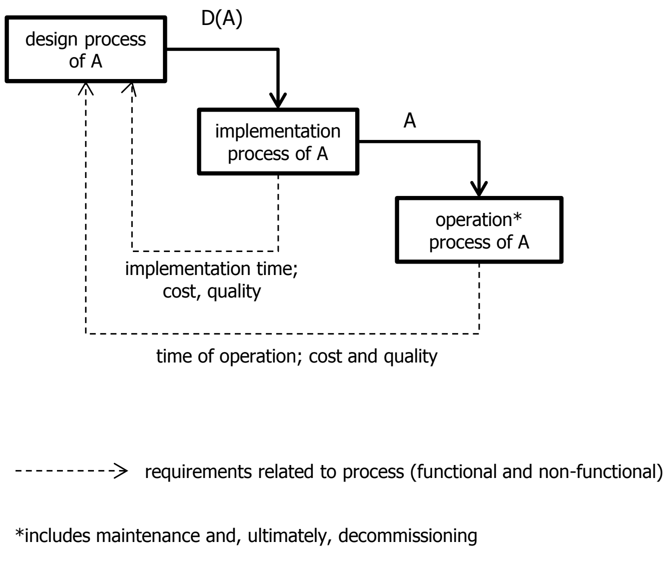

Fig. 3. Requirements inform the design process.

In the electronic ticketing example, it is necessary to take into account requirements related to the implementation process of a new ticketing system, an example of which could be that passengers should be aware of the system change. Although this seems obvious, this can be overlooked when the different processes are not distinguished.

Decision making processes require an institutional structure

As can be seen in the electronic ticketing example, the processes themselves will contain processes. A decision making process can be part of any process. For example, one of the operational processes, the process of acting as a clearing house, consists of a process about which party receives which amount. Decision making processes will also be part of processes within the design process. For example, decision making is part of the identification of requirements for an electronic ticketing system. Since a decision making process requires rules for making decisions, a decision making process will require an institutional structure.

Figures 2 and 3 which show the different processes are highly simplified. Not only do the processes themselves consist of many different processes, as described above, there is also a nestedness of the structures and processes. In addition, there will often be different concurrent processes, during design, implementation as well as during operation.

Systems thinking applies to any artifact (technical or institutional)

Systems design methods specify activities that are carried out during the systems design process. These design activities (e.g. requirements identification, preliminary conceptual design) are usually illustrated for largely technical systems, instead of the socio-technical systems that we focus on. We argue that the system design phases apply to any artifact, whether it is technical or institutional. Both technical as well as institutional artifacts have to be designed in such a way that they fit within their environment; physical artifacts have to be embedded in the physical environment and institutional artifacts have to be embedded in the institutional environment. The building blocks/components of the design and the actual designs are of a different nature. The design of a technical structure will consist of technical drawings/descriptions and the design of an institutional structure will consist of rules on paper. The actual artifacts will also be different in that the technical structure consists of physical matter and the institutional structure consists of rules in use (Fig. 1). However, the phased systems approach to designing the structure can be the same.

A requirements analysis can be conducted for both processes requiring a technical structure and as well as for an institutional structure. This was shown above in the functional decomposition of the electronic ticketing system, where some functions were technical and some institutional. Subsystems and components can also be recognized for institutional structures. The basic components of institutional structures are rules. As is the case for technical components, standardisation is often desirable for institutional components. A model contract is an example of a standard institutional component. As a matter of fact, standards themselves, including technical standards, are institutions which enable reuse of components.

4 Corollary: design of a design system

A design system in operation produces a design process

In Fig. 2, which distinguishes the different processes, the design process was shown as the first process. This process leads to the design D(A). Since the design process of A is also a process, one would expect some structure in Fig. 2 that, when placed in a design context, produces the design process of A. As Westerberg et al. (1997) argue, design processes should also be designed. This becomes clearer if we consider the *design system* for A as a second artifact B.

A design system is the artifact which structures a design process. It is a structure which, when placed in a context of capable people and adequate resources should produce the design process of A (see Fig. 4). The design process of B (i.e. the very first process in Fig. 4) will then be the design process which produces the design of structure D(B). When it is implemented, the design system in operation will be the design process of A.

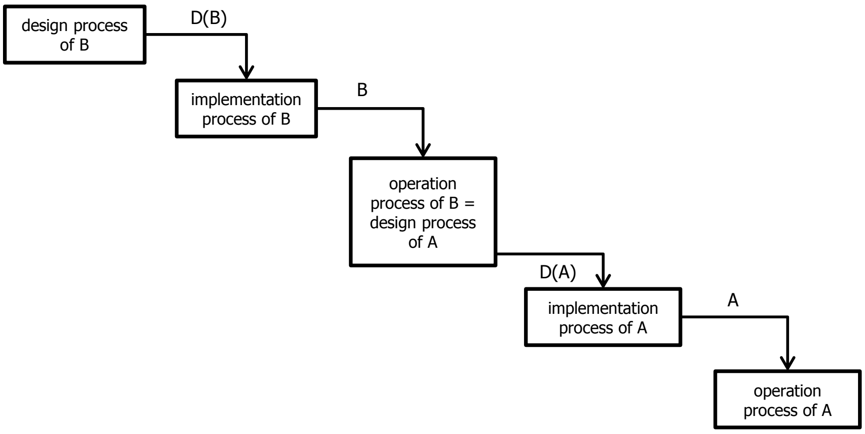

Fig. 4. Designing a design system (B) for the design of a system (A).

The design process as a decision making process

A design process can be seen as a decision making process (see e.g., Simon, 1992; Parnell et al., 2011). During the design process of A, decisions are made about the structure of intended system A. As was argued above, institutional structures are needed to produce decision making processes. This means that an institutional structure is needed to shape the design process of A. Being the structure for the design process of A, D(B) will be an institutional structure consisting of, for example, rules specifying which models, methods, and tools to use, and which people to involve in the design of the system, for which activities, and at what time. These will then be implemented, and when they have been put into place the design process of A will be produced.

An institutional structure to produce the design process

When it is possible to use an existing structure D(B) to produce the design process of A, it is not necessary to design B from scratch. Most systems design/systems engineering textbooks describe a phased approach for systems design. Sage and Rouse (2009) identify seven phases of systems engineering. The first four phases relate to the systems design process and the final three to implementation and operation:

1. requirements and specifications identification,
2. preliminary conceptual design and system-level functional architecting,
3. logical design and physical architecture specification,
4. detailed design of the physical architecture and associated production, and testing,
5. operational implementation of the resulting product or service system in the field,
6. evaluation and modification,
7. operational deployment and maintenance.

We view these phases as sub-processes within the larger process of systems engineering. To shape these processes, structures are needed that, when placed in a context of people (e.g., systems engineers, experts) and resources, guide action so as to produce desired outcomes. (e.g., a set of system requirements for the first sub-process). Sage and Rouse (2009) provide further guidance by positing that each of their seven phases should be structured in (again) seven steps as depicted in Fig. 5.

	Formulation			Analysis		Interpretation	
	Problem Definition	Value System Design	System Synthesis	Systems Analysis	Alternative Refinement	Decision Making	Planning for Action
Requirements and Specifications							
Systems Architecting and Preliminary Conceptual Design							
Logical Design and Functional Architecting							
Detailed Design, Physical Architecting, and Testing							
Operational Implementation							
Evaluation and Modification							
Deployment and Maintenance							

Fig. 5. The 49 element, two-dimensional systems engineering framework proposed by Sage and Rouse (2009, p. 27).

The point we want to make here is that the conceptual model proposed by Sage and Rouse (2009), depicted in Fig. 5, is a structure: a general structure which shapes a systems engineering process. The design of a specific systems engineering process using this general structure, will entail choosing the structures that in turn will shape the processes corresponding to the cells in the framework.

Each of the steps within a phase (i.e., each of the 49 cells in Fig. 5) is a process, and each of these processes requires a structure that will shape them. Such a structure will need to be tailored to a specific process, but existing methods and techniques can be used as building blocks. For example, the method of constructing objectives hierarchies (Keeney and Raiffa, 1993) may be used to shape the process of value system design within requirements identification. The description of these methods includes a symbolic notation and rules on how to apply the method. These rules can be seen as an institutional arrangement. All systems engineering methods are purposeful and rational decision making/problem solving processes, but behavioral rules are needed to make the methods produce relevant output. Additionally, since systems design is conducted in teams (Bucciarelli, 1996), additional behavioral rules are required in order to collaboratively design a system. The relevant institutional arrangement depends on the context.

Existing methods and techniques for systems design can be used as institutional structures which shape a design process. However, in specific contexts these methods may not be suitable or insufficiently detailed. For the design process of a complex sociotechnical system involving many different stakeholders, existing methods will often not suffice, and (part of) the design process will also have to be designed.

In TIP design, the P often refers to designing an institutional structure which structures (part of) the design process, i.e. the P refers to D(B). However, it is important to note that decision making processes can also be part of implementation or operation processes, and therefore speaking about a decision process is ambiguous if it is not clear which life cycle process the decision making process refers to.

5 Summary and conclusions

Our analysis of STS design by making a strict distinction between structure and process has led to a number of insights that help us to refine the TIP design approach. Our premise is that any engineered artifact A is a *structure* that, together with the *context* C in which it is implemented, produces a *process* P that performs the intended function of A. We find that the duality between structure and process is applicable to all processes, and that it can be observed at many different levels. In STS there are always concurrent processes, and processes within processes. By making a distinction between different processes, it becomes clear which structures are relevant. For an artifact to perform its function, its context must feature structures in which the artifact can be “embedded”, and a “drive” that generates the process.

A difference can be made between natural and artificial (or human-made) structures. Artificial structures can be designed; natural structures are always part of the context. Artificial structures are either technical or institutional structures. Technical structures are made up of physical building blocks and institutional structures are made up of immaterial building blocks, consisting of rules for behavior. For both technical and institutional structures the design process will result in structures "on paper" which then have to be implemented. To be effective, designed rules ("rules on paper") have to be adopted and understood by the people: they must become "rules in use" (Ostrom, 1990). This process of adoption of rules can be seen as the implementation process of the designed rules. Transient structures are easily overlooked in discussions on design. Transient structures are structures which shape a temporary process that produces a new structure, such as scaffolding for a building or rules for negotiation to produce a contract.

In STSs there are always concurrent processes, and processes within processes. All processes are bound by structures, many of which are designed. Therefore it is better to speak of design *in* STS, rather than of design *of* an STS. An important key to the SE discipline is that engineers explicitly delineate their focal structure(s)/process(es) (will always be: operation of A('s)). SE is about structuring the design process by means of institutional artifacts (frameworks, approaches, methods) and often also technical artifacts (tools).

The distinction between structure and process shows why the acronym "TIP" in TIP design is somewhat misleading. The T and I refer to structures and the P refers to (decision-making) processes. Decision-making processes are important processes in all phases of a system life cycle. They are themselves shaped by institutional structures which are placed in a context. Since decision-making processes can relate to all phases of the life cycle, it is important to make the relevant phase explicit. The TIP perspective itself is a contribution to the field of systems design in that it explicitly pays attention to institutional design. This paper adds to the TIP design way of thinking by showing the analogies between technical and institutional structures and we argue that systems thinking/systems design applies to any artifact, be it technical or institutional.

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