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Trans-Disciplinary Systems as Complex Systems

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Abstract. The system concept is a widely-used concept in research and practice. Already in the 50s of the previous century, a community was created to investigate interrelationships between domains and create a theory surpassing and comparing domains. The General Systems Theory (GST) community has tried to come up with such a theory for several decades. The ambition has grown more realistic in the years after, recognizing that an all-encompassing theory would not be possible. Since then, systems research was aimed at generating useful and usable approaches to compare and interrelate domains, thus creating a trans-disciplinary approach to enable description and analysis of large, and even complex, systems. The concept of systems, however, is often loosely used. Levels of abstraction are neglected, and interrelationships between systems ignored. In this paper, the concept of system is put in historical context, and further elaborated upon in the context of complex and trans-disciplinary systems. Two examples of transdisciplinary systems are presented and discussed to illustrate the use of the system concept.

Keywords. Systems, system hierarchy, system complexity, trans-disciplinary system

Introduction

Systems and systems thinking take a predominant place in current practice and research. Also the concept of systems of systems is used quite frequently. Systems are encompassing concepts with different structures, aspects, and layers. It is often not clear what actually is meant with systems and whether the concept is used consequently and consistently in academic and industrial circles.

In this paper, the concept of system will be explored based on the discussion found in the literature, including the concept of a complex system. Specifically, we will refer to general systems theory (GST) as already conceived in the 50s of the previous century. Specific attention will be given to trans-disciplinary systems, in the context of trans-disciplinary engineering, as a special example of complex systems. Such systems normally include many subsystems, each of which may be complex also. Subsystems may also be information systems, which are not characterized as complex systems in this paper. However, information systems play an essential role in complex systems like trans-disciplinary systems. The relationships between an information system and the trans-disciplinary system need to be characterized carefully. In this paper, we will make an attempt to do this for two examples.

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By explaining the concept of complex system in the context of trans-disciplinary systems into more detail, the paper provides handles to use the system concept more deliberately in trans-discipinary research and practice.

The paper is outlined as follows. Section 1 discusses the concept of system based on literature already originating in the 50s of the previous century. The subsequent sections present some examples of information systems used in the context of trans-disciplinary engineering. These examples serve to explore complex systems like trans-disciplinary systems, as well as their subsystems, complex and other ones, like information systems, which may be far from simple. Finally, section 5 presents a summary and ideas for further work.

1. What are systems

The concept of system is widely used in theory and practice. However, in many cases it is not very clear what really is meant with system. In an attempt to give a formalized account of a fundamental theoretical issue in general systems research Marchal has given a very elementary definition of a system [1]:

S is a system only if $S = \{E, R\}$, where

(i) E is an element set, and

(ii) $R = \{R_1, ..., R_n\}$ is a relation set, i.e., $R_1, ..., R_n$ are relations holding among the elements of E.

This definition is a very generic one, but can be given content in any domain and on any level. Even systems of systems can be characterized here, when systems on a lower level are seen as the elements of the higher-level system. Relations between elements of a system can be of any kind, e.g., part-of or functional, but also fixed, like in natural systems, or intentional, i.e., created by somebody and existing as long as needed [2].

Any object, artifical or natural, can be viewed as a system. Every such system has a function in its context, like a stone, putting weight on the surface it lays upon or storing and disseminating solar heat. A house is a system with many different functions, depending on the context in which the system is considered.

General Systems Theory [3] (GST) has emerged in the 1950s and describes a level of theoretical model-building that lies between highly generalized constructions of pure mathematics and specific theories of specialized disciplines [4]. Mathematics abstracts away from content and context. On the other hand, disciplines, like physics, chemistry, biology, psychology, etc., have their specific theories and correspond to a particular segment of the empirical world.

General Systems Theory is the result of a quest for a systematic theoretical construct that describes the general relationships of the empirical world. It is not a single, self-contained general theory of practically everything that replaces the special theories of particular disciplines [4]. As Boulding claims, such a theory would be without content. GST seeks a place between the specific without general meaning and the general without specific content. The objectives of GST can be defined with varying degrees of ambition and confidence. At a low level of ambition, but with high degree of confidence, GST can point out similarities between theoretical constructs of the different disciplines. At a higher level of ambition, but with possible lower confidence, it aims to develop a spectrum of theories – a system of systems. Like the periodic table of elements, it may show gaps in theoretical models, which direct research to filling those gaps. This ambition, however, is still not achieved.

The merit of system theory can be found in specifically framing and defining the focus of attention. This can be disciplinary, like a waste treatment model, but also inter-disciplinary, combining two or more different disciplinary systems, like the waste treatment model and the eco system [5]. Of course, such an integrated model is less acceptable to each of the disciplines, but is a compromise to support communication and the search for trans-disciplinary solutions. Trans-disciplinary systems add a level of analysis which does not exist on the level of each of the disciplines [6].

Much discussion can be found in the literature on the concept of complex systems. When we simply count the number of elements, systems with a large number of elements may appear to be rather simple, like the solar system [7], because only a limited number of the pairs of interaction appear to be of significance. In addition, systems that occur in nature are mostly hierarchic and nearly decomposable. Approximations on higher levels are often made possible [7]. The weather system, on the other hand, is still hard to simulate and predict. Much of our perception of complexity may be due to the fact that we base our models on wrong assumptions, like in forecasting models to guide economic policy [7].

For the purpose of this paper, system complexity as defined by Nelson [5] is useful. Nelson defines a complex system as a system having at least two conflicting goals. Such a system always contain human beings, otherwise there would not be goals. Systems functioning without persons have functions to reach the goals of human beings, possibly assembled in societies. The central idea here is intentionality [5].

In the context of transdisciplinary engineering, complex systems, as defined above, are the organizational systems in which multiple disciplines and multiple organizational roles work together to develop new products or services. Such a system consists of many subsystems, which may not be trans-disciplinary but may still be complex. For example, in developing an electro-mechanic product, the subsystems are the electronic design department and the mechanical design department, each with its own processes, its own goals, people, equipment, and knowledge. In the trans-disciplinary system they have a separate, integrated, process, shared people, shared equipment, shared knowledge, and, above all, shared goals. These goals may possibly conflict, requiring negotiation and possibly adaptation of the goals, process, people, equipment, and knowledge. Other subsystems may not be complex, in the sense defined above, like information systems used to manage product and process information.

In the next section we will dive a bit more into the concept of a trans-disciplinary system.

2. Trans-disciplinary system concept

In Figure 1, the system of trans-disciplinary engineering is depicted [8]. It shows the innovation process as the central element of the system. The innovation process is performed by and involves many different stakeholders, such as engineers, designers, manufacturers, marketing and sales people, maintenance. Other stakeholders, like financial institutions, governments and certification bodies, may have a strong influence on the process, but are often not directly involved. The innovation process uses new technology, either from within the company, but more often from outside the company. The trigger of the process may be a new idea, which may range from brakethrough to evolutionary. This idea may concern the product, the market, the process or even the organisation. The process, used knowledge and stakeholders require organisational arrangements, like rules, norms, and contracts, to enable collaboration and protect knowledge misuse and leakage [8].

The product of the innovation process is a production system, which is capable of producing, selling, maintaining and recycling the new product for the intended market. For example, when the product is a new household appliance, the production system is intended to produce, market, sell, maintain or take back the appliance. When the product is an information system, the production system is the software company that maintains and updates the system. It also markets and sells the information system and offers services to customers.

It is clear that the system depicted in figure 1, is a complex system as defined in section 1. It is a system in the sense that it is an element set and a relation set as defined above. Many elements, however, are complex systems, while the relationships are many and highly different in nature. Other elements of a trans-disciplinary system are not complex, like information systems.

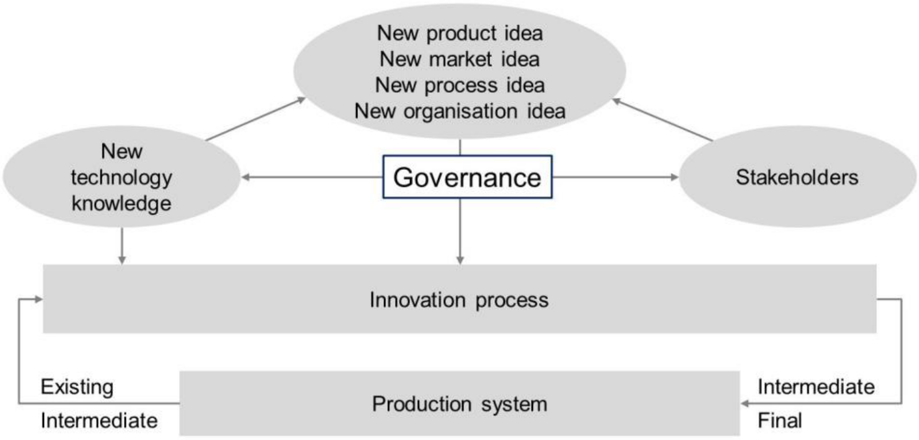

Figure 1. A trans-disciplinary engineering system.

Information systems can be large, with many elements and relationships. They are not complex, however, because output can be predicted from input provided. As soon as humans are involved the system in which the information system is used is complex. Humans may not sufficiently understand the system, this using the system in a way not intended. In addition, the user interface may be difficult to comprehend and use, making users reluctant to use the system in a proper way. Also, users or organizations may have their own goals with the system, like forcing a particular way of working or gaining more power.

There have been attempts to develop frameworks for studying and analyzing complex systems. One example is the soft systems approach by Checkland and Holwell [9]. Another approach is the process model of organizations [10]. Both approaches emphasize that systems thinking supports framing the system of focus. Such models are used to depict a complex system. They are useful to support communication between stakeholders of the system and to identify problems that require further analysis and definition. The system descriptions are not sufficient for problem solving as such, but help to understand the complexity, structure, and context of the problem. Often, problems concern only a subset of the system under study, but may have an impact on the system as a whole. The systems approach helps to see the relationships between problems and between problems and the behavior of the system. Additional theories and methods are then needed to dive into the problem to come up with ideas for solutions. The context of a system is not depicted in Figure 1, but is very important to consider, because system behavior depends on its context as well as impacts upon and influences its context.

Coming back to trans-disciplinary systems, it is important to clearly distinguish the boundaries of the system at hand in its context as well as the internal structure of the system. For example, one may want to focus on a particular phase of the innovation process, for example, the detailed design phase. In this phase, a subset of stakeholders is involved with a more limited number of functional roles and coming from a more limited number of departments or companies. Still, the system under study is complex. The context of this system are the preceding and subsequent phases and the innovation system as a whole.

In trans-disciplinary engineering, information systems are in use, often more than one. These information systems may be used in a particular phase of the innovation process or may be used throughout the whole process. Important questions in depicting and studying a particular phase or two or more phases of the process are, for example:

- What is the main process of focus with its input and output?
- Who are involved?
- What are mutual relationships between people involved?
- Are goals possibly conflicting?
- What are the information systems in use?
- What are the relationships between the different systems, i.e., information systems and organizational systems?
- Who is using which information system for what purpose?
- Are there potential data conflicts?
- Etc.

In the next sections, examples of information systems are presented with their contexts, the complex system in which the information systems are used.

3. Information system: Aircraft maintenance documentation

Aircraft maintenance focuses on multiple, often contradictory objectives. A primary objective of aircraft maintenance is to keep the aircraft in an airworthy state, i.e., a state in which it is safe to operate the asset. Safety of aircraft operations is paramount in the aerospace business. However, this is in potential conflict with another objective of maintenance: to deliver airworthy aircraft at the lowest cost, in order to be economically productive. In theory and in practice, economical pressures may compromise the level of safety which is offered, as evidenced by various studies into human factors in maintenance [11]. A third objective of aircraft maintenance is to minimize time spent, such that the aircraft operator can utilize the asset to the highest extent possible in order to generate revenue. Each of the aforementioned objectives can be associated with a set of stakeholders (e.g., the maintenance company, the airline, the manufacturer (also known as Original Equipment Manufacturer, OEM), national aviation authorities, passengers, air traffic control, etc.).

This multitude of objectives and stakeholders and the associated web of relations contribute towards characterisation of the aircraft maintenance system as a complex system, part of a wider transdisciplinary system which involves various product lifecycle stages as well as expertise from various disciplines (e.g., aerospace, information systems, law). The maintenance system itself is, however, also composed of a great variety of interacting systems and processes.

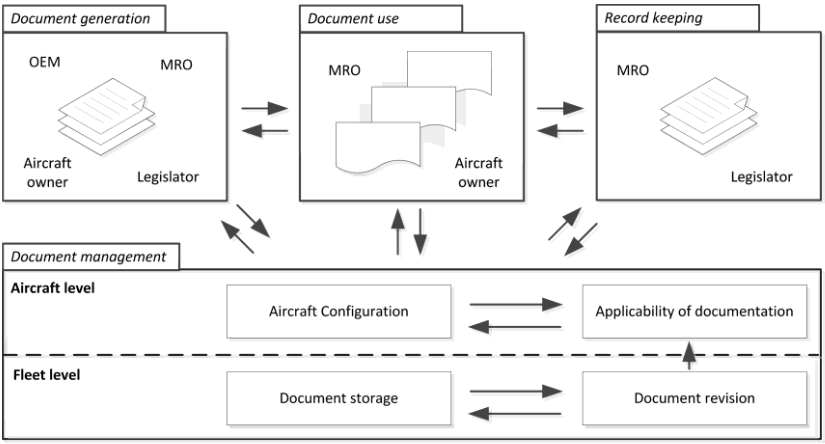

Figure 2. Aircraft maintenance documentation environment.

One example of a subordinate aircraft maintenance system is the aircraft maintenance documentation system. Revisiting the previous questions posed in Section 2, this system can be described as follows:

- **What is the main process of focus with its input and output?** The process focuses on the access, use and generation of documentation to support and monitor the correct accomplishment of maintenance tasks. Inputs are provided by multiple stakeholders towards the maintenance company (MRO): the OEM for instance provides Aircraft Maintenance Manuals (AMM), Troubleshooting Manuals (TSM), Illustrated Parts Catalog (IPC), Service Bulletins (SB), and many more. All of these documents contain pertinent information for task preparation and execution. The legislator provides documentation in the form of Airworthiness Directives, which mandate certain tasks to be accomplished to rectify potentially unsafe items. Furthermore, the aircraft owner and/or operator (frequently the airline) provides inputs towards the MRO as well, such as the Minimum Equipment List (MEL), describing systems and parts which are allowed to fail under strict rectification criteria. On the output side, the MRO generates maintenance records as well as various certificates associated with continuing airworthiness of the aircraft at hand. Traceability of the generated information is critical, as strict regulations are in place towards the historical maintenance records and the governing quality system.

- **Who are involved?** The MRO plans, executes, monitors, and reports on maintenance tasks. The OEM sets constraints in terms of aircraft design itself as well as required maintenance procedures. The airline also imposes constraints in terms of aircraft configuration as well as the time available for maintenance. The legislator controls the MRO, both directly and indirectly, for instance via maintenance record checks and audits of the MRO organisation.
- **What are mutual relationships between people involved? What are the information systems in use? What are the relationships between the systems?** Figure 3 highlights the main elements and context involved in aircraft maintenance documentation, as well as some information systems that are used to govern access to documentation. The documentation process faces additional complications in the fact that 1) significant amounts of additional documentation are generated during the life of the aircraft; 2) the existing documentation is subject to frequent revision; for instance, one European OEM is moving towards a monthly update cycle for its set of documentation, which comprises dozens of documentation types, each consisting of 1000+ pages.
- **Are there potential data conflicts?** As soon as an airline buys an aircraft, the OEM is mandated by contractual terms as well as regulation to share commercially sensitive product information with the airline, and typically the associated MRO. In turn, the MRO generates commercially sensitive maintenance information, which could be used by the OEM to generate and sustain its own after-sales market. However, the regulator does not mandate sharing of information from MRO to OEM, except when safety issues are involved. In practice, it is not uncommon for MROs and OEM to set up bilateral collaborations to explore issues of mutual interest and benefit.

Various research efforts are underway to digitalize and streamline maintenance documentation practices, including access, use and generation [12][13][14][15].

4. Information system: Digital Twin

The Digital Twin is an information system which encompasses the design, validation, manufacture, use, and disposal of both the physical and the digital version of a product developed in a trans-disciplinary system. This product can even be a trans-disciplinary system itself, as is indicated below. The Digital Twin fully describes a manufactured spatial physical product on all necesssary levels of detail (micro to macro). In an ideal case, information on the physical product can be obtained from its Digital Twin. Digital Twins are Digital Twin Prototype (DTP) and Digital Twin Instance (DTI) which operate in a Digital Twin Environment (DTE) [16]. A Digital Twin emerges by four conceptual types of interactions: operations, adaptation, evolution, and profileration [17].

The main elements of the Digital Twin are real space, virtual space, the interconnection of data flows from real space to virtual space as well as from virtual space to real space and virtual sub-spaces [16]. A typical example of Digital Twin is a production environment, which is itself a complex system, a trans-disciplinary system. The challenge is a seamless data exchange between planning and executing domains to enable virtual try-out or simulations of mixed virtual and real data. Such an exchange is still hampered by a lack of standardization on organizational and technological level. Thus, true benefits of synced real and virtual factories are not realized yet [18].

A DTP comprises the prototypical physical artifact. It contains the information sets necessary to describe and produce a physical version that is a twin of the virtual version. These information sets include among others Requirements, Fully annotated 3D model, Bill of Materials (with material specifications), Bill of Processes, Bill of Services, and Bill of Disposal [11][16]. Alternatively, it could be described as a product and process model.

A DTI describes the corresponding physical product to which an individual Digital Twin remains linked throughout the life of that physical product. Such a Digital Twin may contain the following information sets: A Digital Master (fully annotated 3D model with geometric dimensioning and tolerancing), a bill of materials that lists all effectivities, a bill of processes with operations that were performed in creating this physical instance, system metrics with full range of inspection and test results [19], a maintenance log that describes past services performed and components replaced, and operational states from actual sensor data, as well as past and predicted future data [16].

The significant innovation of Digital Twin ensures that performance evaluation is done in the context of the whole product system design, in which the achievement of system design requirements cascades to the design specification of components, subsystems, information integration and standard work by people themselves [19].

A DTE is an integrated, multi-domain physical application space for operating on Digital Twins for a variety of purposes such as prediction (describing future behavior) and interrogation (aggregating data from multiple instances).

In case of a Digital Factory, three building blocks, “Seamless & Comprehensive Product Data”, “Synced Factory Twins” and “Digitized Production” were derived within the framework Digital Twin in Manufacturing [18]. The aim of the block Synced Factory Twins is to ensure that the planning data and simulation models from product development, production planning and production are always synchronized with the values from the real factory. This is supported by two main function blocks: Seamless & Looped Information Flow, and Mixed Simulation Environment (Figure 3).

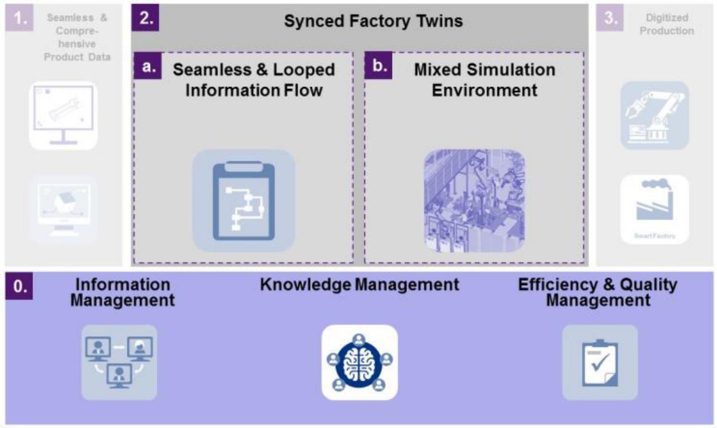

Figure 3. Reference Data Model For Mixed Simulation Environment.

In using a Digital Twin (DT) approach, a product and a product environment can be created without too much waste of time and material. A DT is used in a trans-disciplinary environment in which many different disciplines work together to create a product (environment) that would not be possible by any of the disciplines themselves. A DT approach also helps to support people in making decisions based on simulations and performance estimates. The Digital Factory (DF) is an example of the intimate collaboration between the information system and the trans-disciplinary system in which is is used, in particular the development process in which the DF is developed [20]. Even the role of people in the digital factory should be part of the total virtual and physical design. In sum, in case of the DF, there are three high-level systems to consider [21]:

1. The trans-disciplinary development system, a complex system, consisting of designers, engineers, manufacturing automation people, etc [22].
2. The Digital Twin system, an information system, used to create, manage and maintain data of the virtual production system design and the physical DF design [23][16].
3. The physical DF, which is a complex system, consisting of many production machines, people with more or less standard tasks, and a standardized process.

Each of these systems may have different contexts [24]. Each of them also consist of many layers of interacting subsystems [25].

5. Summary and conclusions

In this paper the system concept has been discussed. Since the 50s of the previous century many researchers have used the concept in an attempt to identify similarities and congruences between different domains. It has become clear that an all-encompassing system theory is too high an ambition. On a more practical level, system research and system thinking have appeared useful for crossing domain borders and enable trans-disciplinary collaboration [22]. Especially in trans-disciplinary engineering, the recognition of a shared goal and the need for cross-domain information exchange require a systemic approach [26].

The concept of complex system has been defined as a system in which multiple goals exist, which may conflict. A trans-disciplinary engineering system is, hence, a complex system. The shared goal is not a fixed one. It may shift during the process due to the differences in and evolution of goals of the many stakeholders.

In a trans-disciplinary engineering system information systems are used to create, manage, exchange, process, and maintain the many data, models, and documents. These systems are indispensable to support, among others, the decision-making processes of the people involved in the trans-disciplinary engineering system [22].

It is important to clearly distinguish the many systems that make up the trans-disciplinary engineering system as well as the levels on which they operate or function [26]. With this paper we have tried to support a more explicit use of the system concept.

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