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Quantifying the Complexity of Socio-Technical Systems – A Generic, Interdisciplinary Approach

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Abstract

In the last decades, much effort has been invested to explore the phenomenon of complexity, aiming at a better understanding of systems to be able to cope with today's challenges of Systems Engineering. Most of the published approaches and methodologies assume complexity only as a system property and neglect human perception and interaction within the system. Therefore, we combine the Systems Engineering perspective of complexity with results from psychological research and present an interdisciplinary approach to describe and quantify complexity in socio-technical systems. This contribution supports Systems Engineers during the whole system lifecycle by pinpointing the technical and social variables which lead to complexity.

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Keywords: Perceived complexity, complexity potential, quantification, socio-technical system

1. Motivation

In times of rising dynamics inside and beyond systems, understanding system lifecycle properties (cp. de Weck[1]) and being able to precociously control them has become a major goal in systems' design. Numerous research studies from different disciplines have already explored this field. There are just as many approaches for describing and coping with complexity as there are different, underlying definitions of complexity. The specific disciplines that deal most extensively with complexity in a typical sense and have produced the pioneering research contributions are: Systems Engineering and Psychology. In System Engineering research, complexity is mostly studied as a kind of system property that should be described, assessed, and controlled. In contrast, Psychology characterizes complexity as a

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phenomenon that occurs in the context of tasks, problems and situations. Due to the speed of technological progress, humans are often the limiting factor in agile systems. Thus, planning and developing the whole socio-technological system has become much more important, with the role of humans needing to be characterized and integrated into the approach of complexity management. This contribution opposes essential findings from both research fields and discloses the existing research gap (section 2). Therefore, we develop a general description model (section 3) and a generic quantification approach for complexity in socio-technical systems (section 4). Using a brief example from the automotive industry, we demonstrate the usability of the approach in section 5.

2. Complexity from two different perspectives

Based on the described problem, two disciplines can be derived, which deal with complexity in a social, technical, or just in a socio-technical manner. Current publications and respective literature from Systems Engineering and Psychology show that the mentioned topics were largely studied separately. Our literature review confirms the statement from Read[2], that the predominant part of complexity literature considers either mathematical or natural scientific systems. Technical systems, which can be extremely heterogeneous, only pose a peripheral area of complexity research. In the following subsections, we give an overview of the essential and relevant aspects of scientific findings.

2.1. Complexity in System Theory

To give a brief outline of the most important basics from a system's theoretical perspective on complexity, we must first highlight the characterizing aspects, show similar and related terms, and lastly present some classification schemes. It turns out that various aspects are named to characterize complex systems. Thereby it is astonishing that no author has used all detectable characteristics, but only a set of aspects depending on the goals of research. Characterizing aspects are: the system size / quantity of elements, variety of elements, interconnectedness, disorder, dynamics, information content, uncertainty and the system structure (cp. Haberfellner et al.[3], Magee and de Weck[4], Colombo and Cascini[5], Hitchins[6], ElMaraghy and ElMaraghy[7]). Overviews are given by Schöttl et al.[8] and ElMaraghy et al.[9]. Wade and Heydari[10] distinguish the referred complexity definitions in behavioral, structural, and constructive definitions. This reflects the different research perspectives of the mentioned authors.

Due to the term complexity being so ambiguous, related system properties are used, distinguished, and super- or subordinated in diverse ways. Maurer and Maisenbacher[11], as well as Cotsaftis[12], distinguish between simple, complicated and complex systems. ElMaraghy et al.[9] extends this scheme with chaos on top of the scale. Others like Wade and Heydari[10] understand complicatedness and complexity as orthogonal dimensions.

A similar picture emerges with classification schemes. Here, we depict three often cited authors. Manson[13] distinguishes between deterministic (chaos theory), algorithmic (mathematics and information theory) and aggregated complexity, whereas the latter describes the interplay and behavior of the complex system. Suh[14] poses the existence of four complexity types: real, imaginary, combinatory, and periodical complexity. Last but not least, Sinha[15] understands complexity as system property, focusing on the time dependence and distinguishes actual, essential, and perceived complexity.

2.2. Quantification approaches of complexity in technical systems

Few approaches were developed that try to quantify system complexity. Merely all of them strongly depend on specific problems. In general, one can distinguish between approaches that are based on information theory, thermodynamic laws of entropy, or use basic characteristics of complex systems (cp. subsection 2.1) in various combinations. Some examples will be given:

A strict mathematical approach for quantifying structural complexity is presented by Sinha[15]. In his approach he uses system components and interfaces characterized by their quantity, maturity, and type, as well as the type of system structure. Hitchins[6] shows two mathematical methods to measure the system's entropy. However, he notes the subjectivity of complex issues is not regarded when using approaches dealing with entropy. Frizelle and Woodcock[16] present a quantification approach within the scope of strategic development of production systems. They reduce complexity to uncertainty and variety and extend their approach with principles of thermodynamics and computer science. Based on that, Scholz-Reiter et al.[17] quote that the system complexity correlates with the amount of information needed to describe it. They present an approach for structural complexity consisting of a complexity vector built by several characteristics from System Theory. Schöttl et al.[8] refined this approach regarding change-induced complexity in production systems.

2.3. The complexity of solving problems

In the field of Psychology and especially within occupational Psychology, one finds the term "complexity" quite often. It is used in the context of problems, tasks, and situations. One line of research that brought major findings is called: "complex problem solving". A broad overview is given by Fischer et al.[18]. In this case, no common or coherent definition of complexity or complex problem can be found. But Fischer et al.[18] characterize the complex problem by: Intransparency of the situation, politely of the task, interconnectedness of the variables, dynamics of the system, and complexity of the structure.

For the quantification, the essential characteristics which affect the complexity of problem solving have to be identified. For this purpose, Funke[19] quotes system attributes, situation attributes, and person attributes. According to Dörner[20], influencing parameters for handling complicated problems are structured knowledge of the acting person, their idea of the situation, and subjectivity. Furthermore, Dörner[21] postulates that quantifying complexity only by the quantity of attributes and their connection does not fulfill the multilayered requirements of a measurement approach.

2.4. Complexity in socio-technical systems

In conclusion, one can state that there is a broad base of research findings. But several approaches from Systems Engineering and Psychology clearly show deficits and advantages. The elaborated aspects are compared in figure 1. It becomes clear that general characteristics are matched very well and specific aspects have the opportunity to complement each other.

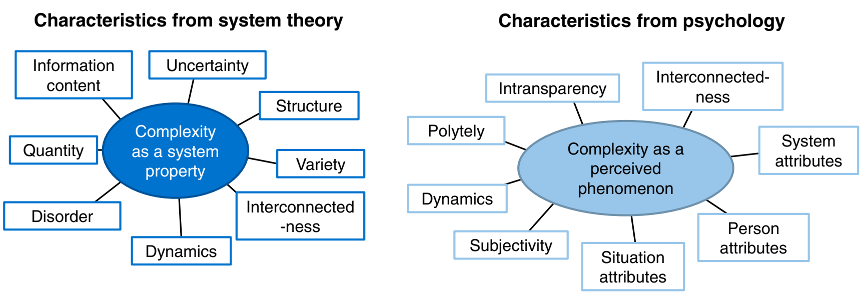

Fig. 1. Comparison of complexity characteristics in System Theory and Psychology

For example, Read's[2] work shows a broadly valid and accepted understanding of complexity, which cannot be transferred to other cases. The definition of complexity according to Suh[14] already suggests the implicit need for integrating the activity of the engineer whilst considering complexity. Sinha[15] explicitly states that technical and psychological perspectives are still insufficiently connected in terms of complexity research. From the psychological point of view, the role of humans in systems changes due to technological changes and progress. In terms of researching complex problems, Funke[19] states that the Psychology of thinking deals with questions beyond its own discipline. Therefore, we recognize a strong need for an interdisciplinary, generic approach to combine the existing findings.

3. Perceived Complexity and complexity potential in socio-technical systems

In this section we present the first part of our approach: a generic description of complexity in socio-technical systems. In order to do so, we combine the significant similarities from the literature review with a coherent understanding of complexity. However, we will not focus on the contradicting assumptions resulting from different research problems. For this reason, the definition of complexity is not considered in the following. We use the term "complexity potential" instead of complexity to allow necessary free space for the mentioned perspectives on complexity. Complexity potential means that the system has the potential to be perceived complex by a person interacting with the system. If we consider the type of interaction and the type of system, the complexity potential of the task arises. Finally, the perceived complexity arises from extending this concept with the person and his or her individual perception. This descriptive model is depicted in figure 2.

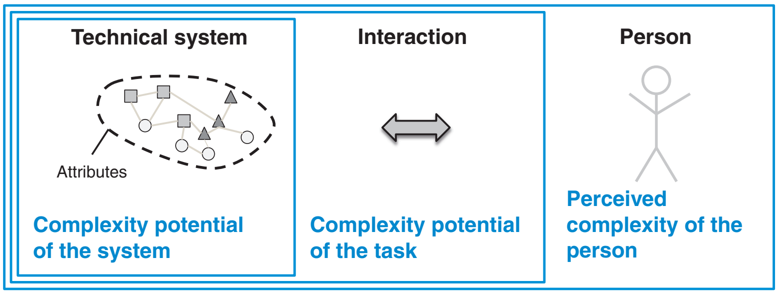

Fig. 2. Representation of complexity in a socio-technical system

To bridge the gap between the theoretical system and psychological quantification approaches, we selected the essential aspects of both disciplines and assigned them to the complexity potentials of figure 2. Some of the highly specific characteristics from Systems Engineering could be substituted with more general ones from Psychology. Subsequently, seven essential aspects for measuring complexity were derived. On the other side, there are six characteristics which are assigned to the three complexity potentials. The connection is presented in figure 3.

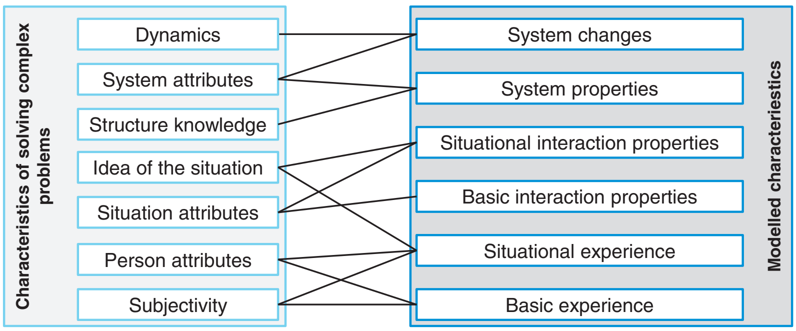

Fig. 3. Representation of literature-based complexity characteristics in the quantification model

4. Quantification approach

The approach for quantifying the complexity potential and the perceived complexity presented here is based on the representation of complexity in socio-technical systems (figure 2) and picks up the characteristics that have to be modeled (figure 3). This results in three top-level factors: complexity potential, interaction type, and perception. All in all, these factors describe the complexity perceived by a person interacting with a system. With our approach, on the one hand we follow the stress-strain concept according to Rohmert[22] that comes from ergonomics. The multiplication of external stress with the personal constitution results in the individual strain. On the other hand, we followed the Risk Priority Number (RPN), a well-known assessment tool, used in Failure Modes and Effects Analysis (FMEA), in order to establish a scale for numerically assessing complexity. The result of our research and its interdisciplinary, generic quantification approach is depicted in figure 4.

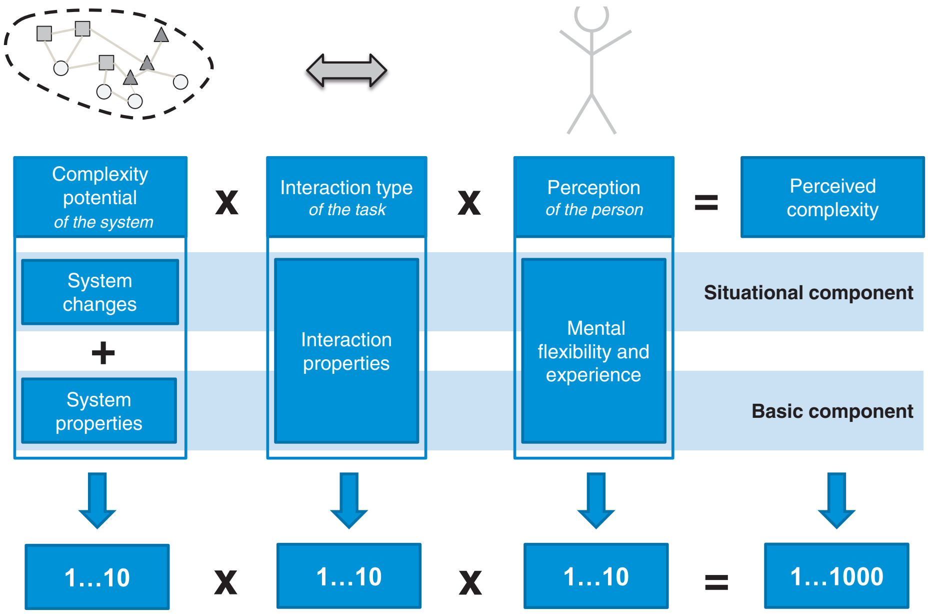

Fig. 4. Quantification approach for perceived complexity.

Each top-level factor consists of a basic and a situational component, in order to accommodate the consideration of section 3. The complexity potential of the system includes system properties as basic component plus system changes as a situational component that represents dynamics. The interaction type of the task is characterized by interaction properties which combine both components. Similarly, the perception of a person consists of experience and mental flexibility. A detailed description of the parameters underlying each factor will be given in the following subsections. To derive the value of perceived complexity one has to multiply the values for the complexity potential (CP), the interaction type (IT) and the perception (P). Each factor is within the range 1 to 10 and the value of perceived complexity (PC) can be found between 1 and 1000. Equation (1) shows the correlation between the mentioned parameters.

$$PC = CP * IT * P \tag{1}$$

4.1. Complexity potential of the technical system

The complexity potential of the system, a person is interacting with, is the first and most important building block of the quantification approach. This factor is modeled by established system properties from Systems Engineering and System Theory literature. These properties are used to describe the static state of a system, which represents the basic component of quantification. The description of system dynamics is based on the identical system properties and represents systems changes. Both components were already presented by Schöttl et al.[8] in a similar quantification approach for systems, named capacitive and dynamic complicatedness. With insight to the presented literature review, we use discrete system parameters to model the system properties and changes so that they may be identified in each system lifecycle phase. Consequently, the opportunity is provided to system engineers to apply this approach in each planning and developmental phase, as well as during system operation. Table 1 lists the mentioned system parameters and related values and weightings.

Table 1. System parameters, values and related numerical values to system properties and changes.

<table>
<tr><th></th><th>System parameter</th><th>Abbr.</th><th>Parameter value</th><th>Numerical value</th><th colspan="2">Weighting</th></tr>
<tr><td rowspan="5">System properties</td><td>Number of elements (processes and resources)</td><td>NE</td><td rowspan="11">Little/low - much/high</td><td rowspan="11">1 - 10</td><td>0,08</td><td rowspan="5">0,4</td></tr>
<tr><td>Variety of elements (processes and resources)</td><td>VE</td><td>0,09</td></tr>
<tr><td>Degree of interconnectedness</td><td>DI</td><td>0,02</td></tr>
<tr><td>Number of interfaces to neighboring system parts</td><td>NI</td><td>0,25</td></tr>
<tr><td>Variety of interfaces to neighboring system parts</td><td>VI</td><td>0,07</td></tr>
<tr><td rowspan="6">System changes</td><td>Change in number of elements</td><td>ΔNE</td><td>0,06</td><td rowspan="6">0,6</td></tr>
<tr><td>Change in variety of elements</td><td>ΔVE</td><td>0,01</td></tr>
<tr><td>Change in degree of interconnectedness</td><td>ΔDI</td><td>0,20</td></tr>
<tr><td>Change in number of interfaces</td><td>ΔNI</td><td>0,03</td></tr>
<tr><td>Change in variety of interfaces</td><td>ΔVI</td><td>0,06</td></tr>
<tr><td>Change of elements (processes and resources)</td><td>ΔE</td><td>0,13</td></tr>
</table>

Due to our industry cases underlying this approach, we have already specified system elements and defined resources and processes. For other fields of application, different element types may be defined. According to the denoted scales in the last rows of table 1, the listed parameters have to be defined and assessed. Precise numerical values, e.g. a high number of interfaces that results in a value of 10, strongly depend on the considered system. Therefore, we do not present a quantitative scale. The weighting of the parameters also depends on the system, ergo, table 1 includes exemplary values derived from a study we conducted in the production planning within the automotive industry. Equation (2) concludes the listed system parameters and the denoted weightings to provide an easy calculation.

$$CP = 0{,}4 * (0{,}08 * NE + 0{,}09 * VE + 0{,}02 * DI + 0{,}25 * NI + 0{,}07 * VI) + 0{,}6 * (0{,}06 * \Delta NE + 0{,}01 * \Delta VE + 0{,}2\Delta * DI + 0{,}03 * \Delta NI + 0{,}06 * \Delta \mathrm{VI} + 0{,}13 * \Delta \mathrm{E}) \qquad (2)$$

4.2. Interaction type of the task

Interaction properties for the type of interaction of the task include a situational and a basic fact component, which are universally valid. The interaction properties are built up from particular influencing parameters which describe the interaction between the person and the system in the context of perceived complexity. These influencing factors characterize the task itself and its interfaces to additional persons. The latter is especially important for the investigation of group work. In particular, tasks are characterized by: Time pressure, demand, content, level of detail, responsibility, number of subordinated employees, work flow, and instructions. Interfaces are characterized by: Localization of communication partners, language of communication partners, and number of communication partners.

Due to relations and weightings between the listed influencing factors not being generally definable as well as corresponding literature demonstrating contradictory statements from different studies, this issue is not regarded any further. A promising way is to combine those particular parameters to form interaction types, which represent a specific set of influencing parameters. With a view to the addressed problem and the usability in practice, the grouping carries the advantage that only interaction types of practical significance have to be considered and modeled. Hence, there are universal interaction types which reflect the level of difficulty of the task by reference to company structures and various job positions. Table 2 gives an overview of some exemplary types and associated values that are used to calculate the complexity potential of a task.

Table 2. Overview of exemplary interaction types.

Interaction type	Description of the task
1	Easy, low demanding job with clear instructions without any time pressure; marginal interfaces
5	Ordinary, well-structured job with diversified content and medium responsibility
10	Highly demanding job; changing tasks with high time pressure; high responsibility for subordinated employees; several communication partners at international sites

To clarify the briefly described interaction types and to ease the selection, we want to give some helping examples for each of them. Looking at automotive industry, type 10 could be a project leader or the production manager of a factory. Type 5 describes a development engineer for driver assistance systems and type 1 refers to a laborer with different auxiliary activities.

4.3. Perception of the person

According to Bubb and Sträter[23], experience and the length of service in a company are the major influencing factors in terms of situational decision making. Experience serves as a general term for different types of knowledge an acting person can collect during education, daily work, and further education. In case of complex problem solving, knowledge of the system and system structure[19] as well as knowledge of methodologies[24] is needed. Those types of knowledge are built up, complemented, and interconnected by increasing length of service. In contrast to problem solving literature, here both parameters are used in combination to describe the perception of the person. For this reason, our approach uses knowledge of methodologies and the system in a general meaning independent from a specific problem.

When dealing with complex systems, human intelligence is another important and influencing parameter (cp. Fischer et al.[18]). In the context of decision processes, Dörner[25] developed the concept of „operative intelligence“, which intensely focuses the flexibility of perception, cognition, and decision. Based on this concept, we use the term “mental flexibility”, characterizing the ability to flexibly adapt to volatile problems independent from knowledge of the system and methodologies. In conclusion, experience and mental flexibility are the relevant, influencing parameters to characterize the perception of complexity when interacting with the system. A five-step graded scale, ranging from “very low” to “very high” is used to mathematically model both parameters (table 3).

Table 3. Parameter values and related numerical values to characterize experience and mental flexibility.

Personal parameter	Parameter value	Numerical value
Experience / Mental flexibility	Very low	1
	Low	2
	Medium	3
	High	4
	Very high	5

In Psychology, there is disagreement about the interplay between experience and mental flexibility. Adelson[26] argues that experts have less mental flexibility and cling to familiar mental models and known strategies. Fischer et al.[18] quote several examples from literature which suggest that experts are more adaptable to volatile boundary conditions than novices. Reder and Schunn[24] investigated the application of methods in solving complex dynamic problems in an empirical study. They conclude that in terms of identical methodology knowledge, problem solving performance depends on the adaptability of the test persons. This is referring to their flexibility in selecting and applying methods. In this contribution, the mentioned parameters are treated as orthogonal values that can independently be determined for the investigated person.

$$P = -1{,}125 * (E + MF) + 12{,}25 \tag{3}$$

Equation (3) describes the correlation between the human perception (P) of a complexity potential, the personal experience (E), and mental flexibility (MF). The function of human perception is depicted in figure 5 to clarify the correlation. Ascending values of experience (1-5) and mental flexibility (1-5) lead to descending values of perception (10-1). A lower numerical value of perception is synonymous with a greater skill of handling complexity.

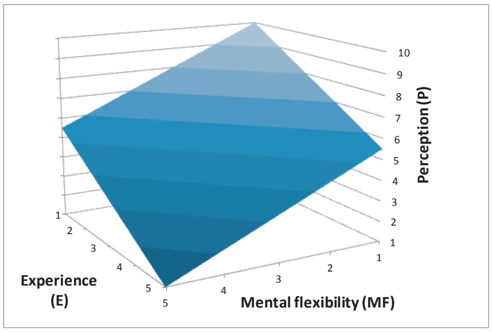

Fig. 5. 3D-Diagram of the perception function.

In some cases, it may be difficult to exactly identify the numerical values of both parameters due to the fact that precise tests for measuring mental flexibility are still missing. Identifying the experience value is much easier, but it depends on the considered system and necessary methods. For industrial use, more fundamental problems occur if one wants to use personal data to make employees simply comparable by their skills. This is the line of reasoning to formulate descriptions of persons for extreme forms of experience and mental flexibility, which can then be used to grade employees (table 4). Consequently, the individual perception can be assessed without any tests by the chief or the person itself, depending on the case of application.

Table 4. Overview of exemplary perception types.

Experience	Mental flexibility	Perception	Description of person
1	1	10	**Dogmatic novice:** Person with little experience, using static paradigms. In cause of changes and certainty, he rapidly becomes overstrained and is unable to methodically solve the problem. Typical patterns of behavior according to Schaub[27] can be observed and the person becomes incapable of action.
1	5	5,5	**Novice with mental flexibility:** Person with little experience, but high degree of mental flexibility. Due to his analytical skills, he is able to cope with changes without becoming stressed. In case of complex problem solving, he remains capable of action.
5	1	5,5	**Dogmatic expert:** Person, using static paradigms. He is not disposed to question well-known patterns of behavior. In case of complex problems, he becomes incapable of action if proven strategies do not work. Typical patterns of behavior according to Schaub[27] can be observed.

5	**5**	**1**	**Expert with mental flexibility:** Person with much experience and a high degree of mental flexibility. Due to his experience of former changes und acting in uncertainty, he factually analyzes the situation and uses specific strategies and methodologies to remain capable of action.

5. Case study

For evaluating our approach which we developed in close cooperation with industry partners, we prepared a case study from the automotive industry. Due to this contribution being focused on the description model and a prescriptive quantification approach, we exclude the derivation of recommendations for action. Thus, the case study is restricted to an application evaluation. The starting point for this considered case is a strategic decision by the company's management. To be prepared for more stringent requirements from environmental regulations, a new combustion engine with less emissions will be developed. The assembly of this new engine has to be done on an existing production line. Taking the perspective of a production planner, we have to quantify the perceived complexity of a workplace in the early phase of product development. At this workplace, the oil pan is screwed to the engine. The new engine gets an oil pan with changed outline, made of aluminum instead of steel. Consequently, processes and resources at this workplace have to be changed, or rather adapted, to the new product. For screwing, a torque controlled screwdriving station is needed so that it can move to the new screw positions. The worker must be able to handle the new device and monitor the changed screwing process. Furthermore, the workplace consists of two additional processes for which one more resource is needed. Table 5 gives an overview of system properties and changes.

Table 5. Overview of case study parameters.

	Abbr.	**Parameter value**	**Numerical value**		**Abbr.**	**Parameter value**	**Numerical value**
System properties	NE	rather low	4	**System changes**	ΔNE	medium	6
	VE	rather low	4		ΔVE	medium	5
	DI	low	2		ΔDI	rather low	3
	NI	medium	5		ΔNI	no change	0
	VI	low	1		ΔVI	no change	0
					ΔE	rather low	4

According to equation (2) and the values listed above, the considered workplace has a complexity potential of ca. 1,7. Afterwards, the interaction type has to be identified. The tasks of the worker are documented by operational instructions and have a rather low difficulty. But the screwing process has to be attentively monitored. Due to the occurring failures having a high range, the task is critical. In addition, there is time pressure because the assembly line is clocked. This results in an interaction type of 5. At least the personal perception has to be defined. The worker has a lot of experience ($E = 4$), since he has already had different tasks related to engine assembly. However, he is known as a person who is not open minded to new technologies and changes ($DF = 2$). According to equation 3, the perception is 5,5. Based on these investigations, the planner is able to calculate the perceived complexity with a value of ca. 46,7 using equation 1.

6. Conclusion and outlook

Although handling complexity is seen as one of the most important challenges for system engineers, there are merely no descriptions or approaches that combine and use these findings from different disciplines. We presented a generic approach based on established, and often cited, fundamentals from System Theory and Psychology in order to bridge that gap. Coming from the assumption that complexity is a perceived parameter in socio-technical systems, which occurs not until a person interacts with a system, we propose the term complexity potential to characterize the system.

In addition, a three-part quantification approach was derived, using well-known parameters from both disciplines, in order to support the systems engineer in making decisions concerning complexity during the whole system lifecycle. A brief case study proves the applicability of our approach in the field of planning production systems in the automotive industry. In case of a high value of perceived complexity, we plan to offer suitable recommendations. Appropriate measures have already been collected and ordered, but relating them to specific complex situations has yet to be elaborated.

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