Design of a Systems Theory Approach for the Evaluation of C2-Systems

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ABSTRACT

The course of large-scale incidents as well as disasters can reveal weaknesses in command and control (C2) systems, which make adjustments necessary. Also, new technologies may require C2-systems to be adapted to achieve their full potential for improving incident command. This paper deals with an approach to enable the comparison and evaluation of different C2-systems or their adaptations in order to find the best possible customizations for C2-systems. To this purpose, systems theory is used to unify the approaches of different research disciplines. Within the C2-system boundaries, distinctions were made to represent three different levels of evaluation: "Physical Characteristics", "Structures and Processes" as well as "C2-system-effectiveness". During the implementation of the evaluation methods from the different research disciplines into the systems theory approach, it became apparent that the comprehensive approach is desirable, but that broad knowledge and expertise is necessary, especially at the highest evaluation level "C2-system-effectiveness".

Keywords

Systems theory, command and control, observation, evaluation

INTRODUCTION

C2-systems are the foundation for leadership, collaboration, decision-making, resource management, communication, etc., in large-scale incidents and crises. In this research approach, the basic documents (for example FwDV 100, NIMS, AIIMS) that define the contents of the corresponding systems are seen as C2-systems. They are used in emergency management, for example by the fire department, the police or international aid organizations, as well as in the military and in private industries. Depending on their place of origin, C2-systems include systemic, social, cognitive and technical components. Systemic components can be, for example, structures as well as processes of the specific organization. Well-known examples of structures are C2 hierarchies that strictly define command and reporting chains. Famous processes are management flows that specify work steps from the acquisition of information to the implementation of measures. In all C2-contexts, however, human beings are a fundamental system component. The human being works in the C2-systems and puts into practice the fundamentals specified therein. For this reason, some C2-systems also include social components such as choosing the correct leadership style. Other systems go even deeper and also include cognitive aspects such as analytical or naturalistic decision making as well as known errors in decision making. In rarer cases, the documents already define and describe technical systems that human beings work with to effectively implement processes. For example, computer programs that support the visualization of the situation or the command structure can be mentioned here.

From time to time, C2-systems have been adapted on the basis of experience or scientific findings. Early on, especially in the military context, there were stakeholders who thought about the strategic, tactical and operational improvement of C2 in order to gain an advantage in warfare as well as combat. An early example of this is

philosopher, strategist and general Sun Tzu, who lived in China around 544 BC and wrote the work "The Art of War." In 13 chapters, it summarizes thoughts ranging from strategy, to maneuver, to the importance of terrain, to the use of spies (Sun Zi and Senger, 2021). However, unlike the work "On War," which was written in the early 19th century and authored by Carl von Clausewitz, "The Art of War" is quite small in scope. The contents of Carl von Clausewitz were mainly taken from his own experiences and observations. However, his conclusions still have an impact on leadership training and the development of C2-systems worldwide. Among others, the principles such as ordering space and time, forming reserves or friction are worth mentioning (von Clausewitz, n.d.).

From these historical examples, it can certainly be seen that observations and lessons contribute to the adaptation of C2-systems. This thesis can also be confirmed from the recent past. For example, the U.S. Incident Command System (ICS) was developed in the 1970s following devastating wildfires in California. Investigations into the wildfires revealed that neither a lack of or inadequate equipment nor the number of units caused this operation to become out of control. Rather, it was a lack of organizational structure, different terminology and processes and a lack of coordination at the strategic level. As a result, through the Firefighting Resources of Southern California Organized for Potential Emergencies (FIRESCOPE) working group, the cornerstone of the ICS was published in 1974 under the name “Field Command Operations System Conceptual Design Description." Today, the ICS has been implemented into the National Incident Management System (NIMS) of the United States of America and continues to evolve (Emergency Management Services International, Inc., n. d.).

The impetus for the German “Command and Control System in Emergency Operations” (FwDV) 100 also lies in the 1970s, due to the disastrous “Heidebrand” (vegetation fire) in 1975. The report on the vegetation fire disaster in Lower Saxony made it clear that there was a lack of a uniform, nationwide C2-system (Deutscher Städtetag, 1976). In this respect, clear parallels can be drawn here with the development of the ICS - both developments were driven by identified deficiencies in incident command for large vegetation fires.

Another industry also demonstrates the development of new concepts and methods to counter leadership failures. The aviation industry developed "crew resource management" (CRM) after investigating numerous aviation accidents and after it became increasingly clear that the job of "pilot" was no longer a pure craft, but also included large components of a team and systems manager. With the development of highly reliable jet engines and redundant systems, technology was no longer the primary cause of aviation accidents; it was now people. The intention of introducing CRM was to promote leadership and synergy of teamwork to minimize human error. While CRM cannot be declared as a C2-system, it is more of a leadership culture - but this concept was also developed from the impetus of negative events and reports (Anca et al., 2010).

The presented system theory approach does not yet exist in this form. C2-systems are evaluated, but often only a previously defined component is observed, which corresponds to a specific research discipline. In contrast, the approach presented in this paper takes a broader starting point that can allow identification of strengths and weaknesses of a C2-system. These strengths and weaknesses can then be further investigated using more in-depth methods from different research disciplines. The primary goal of the approach is to compare new C2-systems with previous versions in order to be able to scientifically confirm the intended improvement.

RELEVANCE

Yet recently, some disasters have shown that C2-systems need an overhaul. For example, the 2021 storm disaster in western Germany in which over 180 people lost their lives. The lessons learned from the disaster show that adjustments are needed in command structures and processes as well as in training (Bundesministerium des Innern und für Heimat [BMI], 2022). Another factor that also causes the need for further development of C2-systems is the progress in technology. New devices and software enable a completely new approach to information processing, which can streamline and improve processes. C2-systems need to be adapted along with the new possibilities of technology, which is similar to what is being done in many commercial enterprises as part of digitization. If this is not done, it is lost potential.

If possible, these further developments should be based on scientific evidence. It makes sense to test adaptations beforehand in a controlled environment and consequently to validate that they can provide a benefit in the future. On the one hand, these tests and validations ensure that the adaptations are correct. On the other hand, they can ensure greater acceptance among the people who will later work within the C2-systems. Especially for practitioners, it is important that the test and validation of adaptations of the C2-system are easy to perform and observe. The researchers at TH Köln have therefore addressed the possibilities of simulation, observation and analysis and show the initial findings for carrying out appropriate evaluations.

THE OBSERVED SPACE OF A C2-SYSTEM

C2 research is very complex and it can be necessary to bring together knowledge from different scientific disciplines. Therefore, we operate in the so-called systems theory, which focuses on transdisciplinary knowledge and brings together different research approaches to ultimately achieve an overall result (Ropohl, 2012). For this reason, it must first be determined where exactly the boundaries of the system to be observed exist and which components within this system should be observed.

Boundaries of the C2-System

What is still subject of the evaluation and what is not part of it? This question must be asked in the area of C2 in emergency response. What needs to be addressed within the C2-system and can be observed and possibly optimized? NATO has defined clear boundaries when assessing C2-systems. These refer to

- physical characteristics (Dimensional Parameters - DP) present in the C2-system,
- internal structures, characteristics and behavior of the C2-system (Measures of Performance - MoP),
- effects of the C2-system on working methods and effectiveness (Measures of C2 Effectiveness - MoCE),
- the mission fulfillment of the forces led (Measures of Force Effectiveness - MoFE),
- political and societal outcomes (Measures of Policy Effectiveness - MoPE) (NATO, 2002).

If the C2-system is viewed from a cybernetic perspective, it is easy to show which components are actually still within its sphere of influence (dashed line in Figure 1). Cybernetics is concerned with the study of systems of any kind that are capable of receiving, storing and processing information and using it for control and regulation (Thomas, 1978). A cybernetic system contains the variable to be controlled, a sensor, the controller as well as the target variable and the actuator (Cube, 1972). As shown in Figure 1, these theoretical considerations can also be applied to the C2-system context.

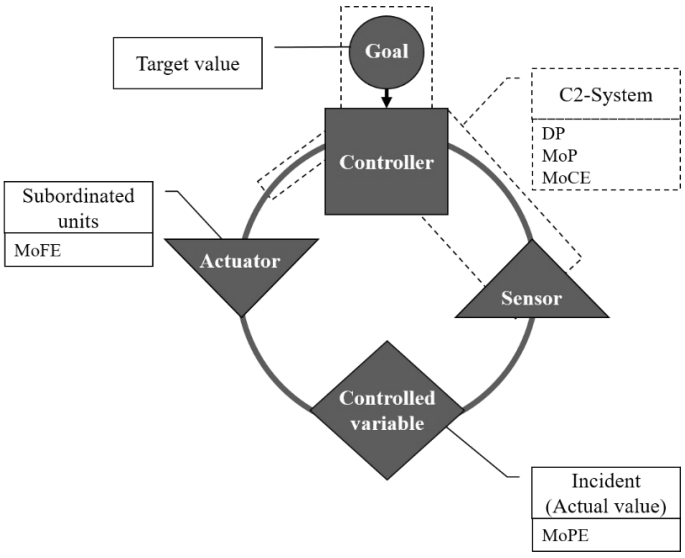

Figure 1: Integration of the C2-system in the cybernetic context

The controlled variable represents the emergency operation or event that must be handled. The sensing element represents all the components of the C2-system that are used to acquire information. The controller is the C2-system itself. Here all information is stored and processed until it is passed on to the actuator for implementation. This can take the form of a command or instruction, for example. The actuator represents the subordinate responding units, which implement the instructions and directly affect the event. A clear distinction must be made between the performance of the C2-system and the execution performance of the controlled units. For this reason, it is not purposeful to consider the overall result of incident response. The boundary of the C2-system must be set at the MoCE and MoFE interface. As can be seen in Figure 1, the area of the C2-system is extended on a part of the connecting line to the subordinated units. The inclusion of this area follows the consideration that the effectiveness of the transmission of the commander's (or command teams) intent should also be considered as an element of the C2-system (Hone et al., 2007; Leggatt, 2004).

A simple example will illustrate this need: Incident command may have performed very well in terms of incident

control, but subordinate units do not implement incident command decisions according to instructions. This ultimately has a negative impact on the overall result of operative response, without the fault of the incident command, which works within the C2-system. It also can be the other way around. In particular, when the subordinate units have large amounts of freedom to fulfill orders. Operational subordinate units in this case can compensate for poor incident command. Therefore, in order to study the performance of a C2-system with a comprehensive approach according to the system theory, physical characteristics, internal structures as well as the system behavior and the effects of the C2-system on the working methods and effectiveness should be evaluated.

Observable Components

As already mentioned, systems theory thrives on a variety of different research disciplines and research approaches. This is also reflected in the tools that can be applied to evaluate a C2-system. They can be at a very simple level, describing only physical properties of the system, to very complex research approaches that require deep expert knowledge to conduct the research. The simplest approach to observe the properties of a C2-system is to collect the physical characteristics that provide the relevant basic structure of the C2-system. For example, the number of available computer units, the available bandwidth for information transmission, the network security standards used, or interfaces. The next approach to evaluate a C2-system is to observe the internal structures and processes as well as their behavior. These are mostly quantitative values such as the time needed to transfer information or process a task. Likewise, this can include observations that view a C2 structure as a network to determine the number of information inputs and outputs at a particular node. In the hierarchy of components to be observed, C2-system-effectiveness is at the top. The most profound insights can be gained by observing C2-system-effectiveness, but the corresponding data are difficult to collect and evaluate because they are on a social and cognitive level. In this context, for example, characteristics such as situational awareness or workload should be mentioned. The next section will identify possible methods that can be used to evaluate these three different components. Table 1 summarizes the different observable components within the C2-system, followed by corresponding examples.

Table 1: Overview of observable components with corresponding examples

Observable Component	Examples
Physical Characteristics	Bandwidth
	Connectivity
	Computing capacity
	Number of PC workstations
Structures and Processes	Time to complete a task
	Time to process a set of tasks
	Time to transfer an information
	Number of information inputs and outputs
	Number of tasks piled up
	Number of interactions with a device
	Number of personnel required for task
C2-System-Effectiveness	Situational Awareness
	Workload
	Sensemaking
	Synchronization of effort
	Communication
	Leadership

METHODS FOR DATA ACQUISITION AND EVALUATION

The methods described are primarily intended to compare two or more systems with each other. This makes it possible to determine whether a new customized system can show improvements over a previous version. An example will demonstrate this possibility of comparison: Command staff has access to live images from a drone in the incident command post during a vegetation fire. The aim is to investigate which constellation of information

processing produces advantages in logistics planning. In constellation A, the live drone images are only available to the planning section. This section preprocesses the information from the drone images and passes this processed information on to the logistics section. In constellation B, a video wall is used in the command post and the live drone images are available to all sections, but in non-preprocessed form. The aim is to compare which constellation better supports the work of the logistics section. Depending on the evaluation purpose, different components can be selected to be observed and evaluated. In the previous described case, for example, it may be useful to focus on components such as "Time to process a set of tasks", "Number of information inputs and outputs" and "Situational awareness", since the aim is to investigate under which constellation the logistics section can process tasks faster because it has increased situational awareness and also has to cover fewer communication needs with the planning section.

For data collection, TH Köln provides a laboratory with technology for observation of exercises or simulations. Primarily, cameras and microphones are used for observation. Depending on the research subject, however, other data such as vital parameters or exact local positions of the participants can also be collected. Appropriate software allows for subsequent non-participant observation by playing recorded video and audio streams simultaneously on a timeline. During subsequent observation, coding schemes can be used to mark and statistically record the objects of observation such as during which time period a specific task was processed or information was transmitted. Figure 1 shows an example of an experimental setup with the observation technology used. The figure is taken from a test in which various work processes for the command staff were tried out.

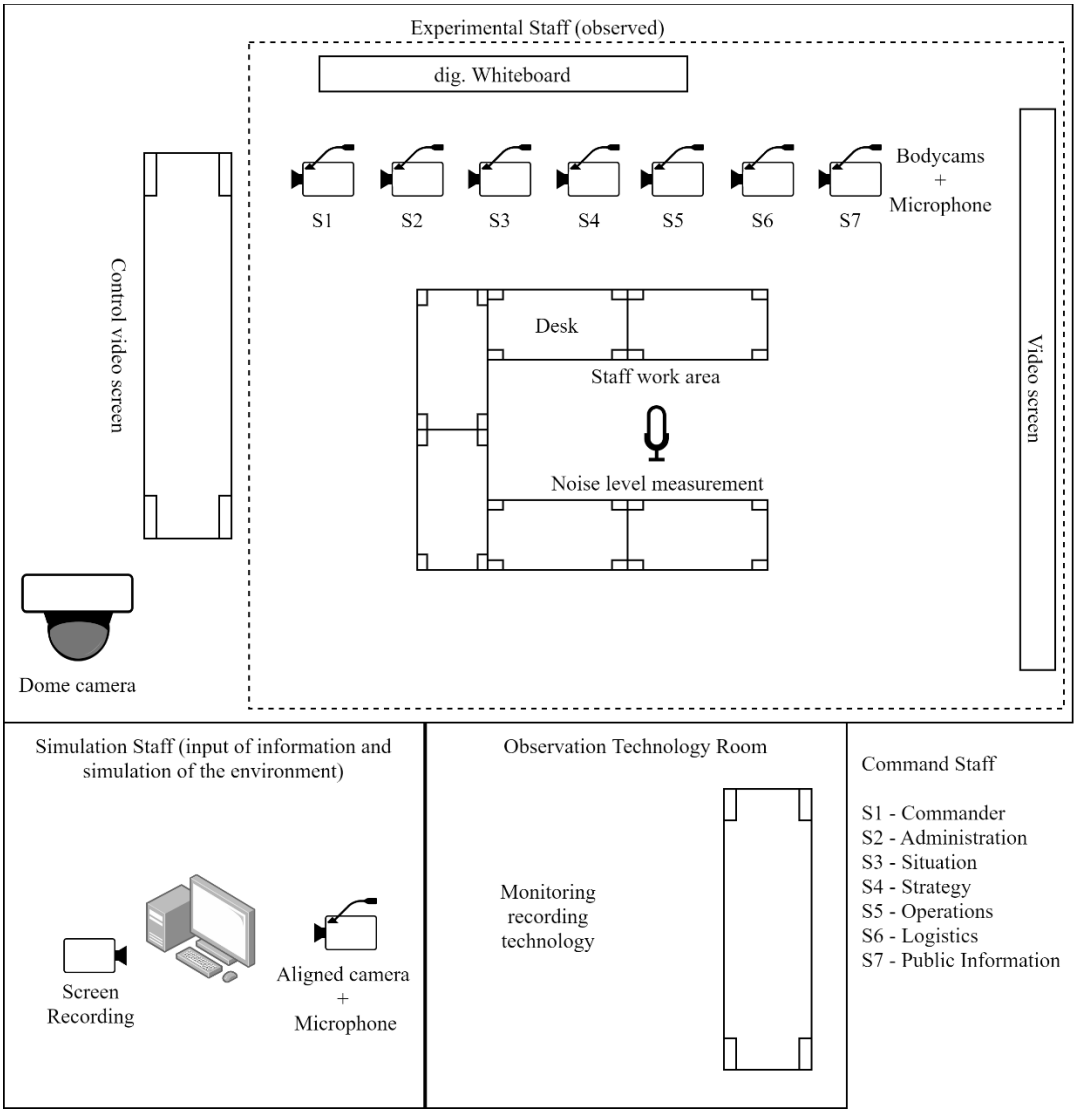

Figure 2: Example of the use of observation technology in a command staff simulation

After data acquisition, the data must be carefully evaluated to draw conclusions about the performance of a C2-

system. For this purpose, the following subsections show the possibilities for data evaluation in the context of systems theory. In the area of C2-system-effectiveness, it is a compilation of a set of methods that have already been developed and tested in the relevant scientific disciplines. In contrast to the evaluation of the physical characteristics as well as to the structures and processes, the methods require a more profound knowledge and a proper expertise in the design of the experiment and the evaluation of the data.

Evaluation of Physical Characteristics

The evaluation of the physical characteristics is based on a comparing method by categories. At the beginning of the comparison, it has to be determined which categories may have an influence on the attributes to be observed. Depending on this, categories are defined by which two or more C2-systems are compared with each other. As previously mentioned, these are properties to which a clear quantifiable value can be assigned. The values can usually be collected before the actual observation, since they come from sources such as data sheets, material lists or predefined plans. If, in the process of observation and evaluation, particularities at the level of structures and procedures or C2-system-effectiveness become evident, correlations or causalities may be identified at the level of physical characteristics. However, since C2-systems are very complex, correlations or causalities do not necessarily exist, and there is no guarantee that they will be identified.

An example of a causality that has constrained a C2-system at the level of physical characteristics can be given from practice: During the observation at the level of structures and processes, it was noticed that the section planning for a simulated vegetation fire took quite a long time for the mapping of the situation. In the end, it turned out that the situation mapping was mainly based on merged mapping photos of a drone. However, the command post was equipped with too little data transfer bandwidth, so that downloading the corresponding photos took most of the time in the process.

Evaluation of Structures and Processes

Evaluation of structures and processes should be limited to simple measurement methods based on time, amount or accuracy measurement. Time and amount-based measurements have a purely quantitative basis while accuracy measurements are qualitative, semi-quantitative or quantitative. Table 1 listed examples of time- or amount-based measurements. The following Table 2 lists examples for accuracy measurements:

Table 2: Examples for accuracy measurements

Measurement	Data type	Example
Quality of decision	Qualitative or semi-quantitative	The decision has positive, negative or no impact on the strategic, tactical or operational objective
Accuracy of a performed task	Quantitative	Setting the current position of a unit on a map
Completeness of information	Qualitative or semi-quantitative	Information passed on includes the relevant content / no important information is missing for the planning or execution of a task
Bias of information	Qualitative	The content of information was transmitted or interpreted incorrectly / the information was transferred without changes due to errors
Quality of transmission of the intent of command	Qualitative or semi-quantitative	The intent of command was transmitted to the executing units in a comprehensible manner and without misinterpretation

The structure and process related measurements can be used to gain knowledge about the behaviors of C2-systems. For example, does the use of a new technology affect how quickly or accurately a task is processed? Or can the restructuring of a command structure possibly result in information being transmitted more quickly? Of course, the appropriate causalities must first be determined, which emerge from the identified system performance. Research results show that this is possible and that system behavior can be drawn from process indicators. By a

network approach and quantifying information transfers, Roberts et al. (2017) concluded that data synthesis tasks should be more evenly distributed among command teams in submarines to avoid bottlenecks in task processing. This approach follows the example in Table 1 of using the number of information inputs and outputs to observe and evaluate the structures and processes of a C2-system.

Evaluation of C2-System-Effectiveness

If the structure and process evaluation level is left to the next higher level, the important element "human being" can also be included in the evaluation of C2-systems. At this level, the focus is on how the C2-system influences human cognition and social behavior. This level requires a great deal of expertise in the relevant field as well as the handling of the necessary research methods (design and evaluation of questionnaires, statistics, etc.). In the literature, relevant aspects that are influenced by the structures and processes of the C2-system could be identified as followed:

- Communication
- Decision making
- (Shared) Situational awareness
- Team cognition
- Workload

For each of the fields listed, there are different approaches for carrying out the evaluation. Often, researchers can choose from several methods that take different approaches. In the field of “communication”, there are research approaches with different focuses ranging from content sharing in a network (Dubé et al., 2011) to understanding words and sentences under difficult conditions (Keller et al., 2017).

The evaluation of “decision making” can be done on a fairly simple level with a rating from correct to incorrect (Dwyer et al., 1999; Elliott, et al., 1997). There are also approaches that take into account the time it takes to make a decision and the available information at the time of the decision (Worm, et al., 1998).

Endsley's situational awareness with the stages Perception, Comprehension and Projection can also be assessed using different approaches (Endsley, 1995). In the research environment of situational awareness, approaches can be categorized, for example, as freeze probe techniques, real-time probe techniques, self-rating techniques, observer rating techniques, performance measures and process indices (Salmon et al., 2009).

Team cognition refers to the team members’ understanding of the processes that are important to the functioning of the team. These include components such as communication, cooperation and coordination. A holistic approach to measuring team cognition is offered by the shared priorities instrument, which is used to measure shared strategic understanding (Berggren, et al., 2014).

A high workload can lead to negative effects on situational awareness as well as teamwork in the C2-system (Berggren, et al., 2014, 2011; Hancock and Warm, 1989). This makes it all the more important to identify which constellations of a C2-system generate too high a workload in order to avoid overloading individuals. NASA developed a tool called Task Load Index (TLX) to measure the subjective workload in different settings. A questionnaire was used for this purpose, which contained items on mental demands, physical demands, temporal demands, performance, effort and frustration (Hart, 2006; Hart and Staveland, 1988).

Only some of the available methods have been listed as examples in this paper. The large and extensive field of C2-system-effectiveness shows how many approaches need to be known in order to select a proper approach. The evaluator must have sufficient knowledge of which methods are available and in which research design they can best be used.

DISCUSSION & FUTURE WORK

As described at the beginning of this paper, the systems theory approach is intended to enable a holistic evaluation of a C2-system that can be easily carried out by practitioners. However, as the development of the different levels of evaluation (physical characteristics, structure and process, C2-system-effectiveness) has shown, it is particularly the highest level that requires extensive scientific expertise in the relevant field.

Further attention must be paid to statistical representative quality. Due to the human being as an important part of a C2-system and the cognitive work in this very system, it is not sufficient to collect the data during only one simulation. A series of simulations with different people must be carried out so that the individual can be excluded as a variable. Depending on the goal and the demand for scientific significance, many simulations may be necessary. Nevertheless, running even a few simulations could reveal certain tendencies that already show differences between observed C2-systems.

Since the systems theory approach to C2-systems described in this paper is quite young, only one experiment on the observation method and evaluation could be conducted till now. In the experiment, a command team had to cope with a given scenario, which took two hours to complete. The observation technique used, as an example shown in Figure 2, allowed a good observation of the structure and process related parameters. The focus of this experiment was on the possibility of observing the level of structures and processes. Observations and evaluations of the C2-system-effectiveness have not yet been carried out. Due to the mass of data collected over the two hours, it has become clear that, depending on the C2-system component being targeted and evaluated, only certain "samples" should be observed, such as those started by a trigger event in the simulation. For example, the time it takes for information (AA) about a critical event (A) to reach the incident commander.

Up to the present time, only a few insights into the practicable use of the systems theory approach could be gathered through the single experiment. In this experiment, the approach was tested exclusively in a pre-defined C2 structure. It is still unclear how well observations can perform in a less structured setting, for example in the civilian sector. Therefore, in the future, further experiments will be conducted that iteratively adjust the observation for usable data analysis. In the long term, a guideline has to be developed together with practitioners, which will enable them to evaluate their own systems.

CONCLUSION

Evaluating a C2-system is extremely extensive and can be divided into different levels of evaluation. The C2-system can be considered as a controller operating between the information acquisition (sensor) and the controlled units (actuator). Within the system boundaries of a C2-system, the classifications physical characteristics, structures and processes and C2-system-effectiveness were made to make a distinction of the evaluation levels. Seen in a hierarchical structure, physical characteristics first enable working in structures and processes. Structures and processes in turn have an impact on C2-system-effectiveness. While the implementation of observation and evaluation at the two lower levels follows quite simple parameters such as physical and quantitative values like bandwidth or time, data acquisition and evaluation at the level of the C2-system-effectiveness is far more challenging. Especially for practitioners who want to check different constellations of C2-systems, it can therefore be useful to first make observations and measurements at the levels of physical characteristics as well as structures and processes. If the impact of the C2-system needs to be examined in more depth and at a higher level, appropriate experts in the field may need to be involved. Nevertheless, findings on the levels of physical characteristics as well as structures and processes can lead to a review of the fundamentals of C2-systems and to adjustments according to observations and analyses in order to optimize the systems and eliminate errors.

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