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MODELLING TRANSPORT SAFETY RISKS: A SOCIOTECHNICAL SYSTEM PERSPECTIVE

Key words: sociotechnical system, systems theory, safety, transport performance.

Abstract: The presented paper discusses the theoretical safety issues in complex sociotechnical systems. The traditional efforts to deal with the accidents/hazard events identification problem for complex systems seem to be insufficient, because they have tended to neglect or omitted the broader sociotechnical environment. Following this, a brief literature review in the area of sociotechnical systems modelling is provided. This gives the possibility to develop a formal model for hazard events (safety risk events) occurrence in man-machine-environment systems. The detailed analysis is provided for the performance of transportation systems.

Modelowanie niebezpiecznych sytuacji w transporcie – perspektywa systemu antropotechnicznego

Słowa kluczowe: system antropotechniczny, bezpieczeństwo, realizacja zadań transportowych.

Streszczenie: Prezentowany artykuł omawia teoretyczne kwestie bezpieczeństwa złożonych systemów antropotechnicznych. Tradycyjne podejścia w celu rozwiązania problemu właściwej identyfikacji zagrożeń wydają się być niewystarczające, ponieważ zwykle zaniedbują lub pomijają szerszy kontekst socjotechniczny otoczenia. W związku z tym krótko przedstawiono przegląd literatury w obszarze modelowania systemów antropotechnicznych. Pozwoliło to na opracowanie formalnego modelu matematycznego dla opisu zagrożeń występujących w układzie: człowiek–maszyna–otoczenie. Szczegółowa analiza została przedstawiona dla systemu transportowego.

Introduction

Today complex systems, such as advanced manufacturing systems, transportation systems, nuclear power plants, or the chemical and petroleum process industry, face increasing economic competition that results in continuous improvement implementation both in quality and in productivity. This trend has led to a greater hazard potential, because unexpected events that threaten safety become more commonplace [37, 46, 48]. Following this, the need for risk and safety management has never been greater.

System safety is usually considered as the characteristics of a system that prevents the occurrence of hazardous events and reduces their consequences if they occur. According to the IEC 61508-0: 2005 standard [14], safety is defined *as a freedom from unacceptable risk of physical injury or of damage to the health of people, either directly or indirectly as a result of damage to property or to the environment*.

According to this standard, many safety-modelling approaches have been developed (e.g., traditional and systemic safety models). For a comprehensive review we recommend reading, e.g., [5, 26, 27, 31, 35]. However, the traditional efforts to deal with accidents and hazardous event identification problems for complex systems seem to be insufficient, because they have tended to neglect or omit the broader sociotechnical environment. The accidents cannot be considered as simply failures of technology alone, nor solely arising from "humane error." They should also be considered as a result of an organisational/environmental context [16, 27]. Thus, system safety analyses should be based on the framework for modelling the technical, human, social, and organizational factors in sociotechnical perspective, including the interactions among system components.

Following this, the goal of this article is twofold. First, it is aimed at the development of a formal mathematical model for hazardous events occurrence in complex sociotechnical systems. Second, the example of safety risk analysis for transportation systems is provided.

The paper is organized as follows: First, the theory of sociotechnical system is briefly described and reviewed. Later, the formal analysis of system's elements with mathematical modelling is provided. This gives the possibility to present the detailed safety risk analysis for transportation systems. The article ends with a summary and directions for further research.

1. Sociotechnical system and its modelling approach

1.1. Sociotechnical systems theory

Sociotechnical systems theory has enjoyed around 60 years of development and application by both researchers and practitioners (e.g., [5, 9, 40] for comprehensive review in this research area). It has been initially developed by the members of the Tavistock Institute in London, with the primary objective to improve the overall quality of working life [6]. For more information, we refer reading [11, 23, 32, 40].

The current review of sociotechnical system theory is given, e.g., in [24, 40]. The system engineering of sociotechnical systems is analysed, e.g., in [18, 25], where the authors define the main interactions between these two theories. The sociotechnical requirements and principles for system design are analysed, e.g., in [7, 20, 36].

Moreover, many approaches to sociotechnical system definition and various models to define the main interactions between its elements have been developed (e.g., [5] for their review). These models describe sociotechnical systems either vertically (e.g., [22, 28]), functionally (e.g., [20]) or by domain (e.g., [45]). Moreover, they identify components of the sociotechnical system mainly in the following three areas: people (e.g., personnel subsystem including workers, remote agents, social system), internal and external environment (e.g., technical environment, work environment, policy and roles, supply chain), and technical subsystems (e.g., tasks, hardware, and software, productive processes). As a result, the term "sociotechnical system" may be descriptive to any practical instantiation of socio and technical elements engaged in purposeful goal-directed behaviour [12, 40].

Based on this general definition, various conceptual approaches to sociotechnical systems development and performance can be defined. Safety management and safety critical issues are among the most important. In this area, there are investigated, among others, workplace safety issues (e.g., [6, 12, 17]), the organizational assessment in complex sociotechnical systems (e.g., [30]), sociotechnical system dependability (e.g., [13, 15]), risk management problems (e.g., [29, 46]), and the use of risk assessment methods/models (e.g., [10, 19, 39, 41, 43]).

The transport safety issues in the sociotechnical perspective are investigated, e.g., in [21] for aviation maintenance, [2] for maritime systems, [44] for traffic safety, or [1, 4, 38, 42, 47], where general-purpose safety models and operational safety issues are introduced. An interesting analysis of sociotechnical transitions influence on strategic transport planning is given in [3]. In this work, the authors focus on the interactions between sociotechnical system's elements with safety modelling, providing an example of safety risk analysis for transportation systems. The presented model is a continuation of research work given in, e.g., [8, 33, 34].

1.2. Formal analysis of system's elements

The subject of the system description analysed in this paper is "a human (decision-maker, operator) – a technical object (mechatronics means of transport) – an environment (technosphere and natural environment)" system (Fig. 1). The aim of the study is the qualitative and formal description of dangerous situations that can occur in such systems. Relatively isolated elements of such systems are human and technical objects. Moreover, humans and the environment are conventionally treated as natural objects, and technical objects and the technosphere are treated as a collection of objects artificially produced.

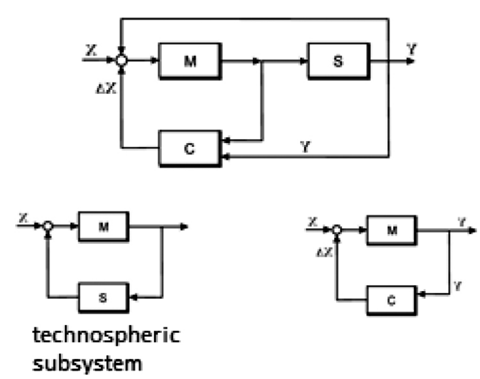


Fig. 1. A sociotechnical system and its main subsystems with elements' interactions (M – technical object, S – environment, C – human)

The environment described in the model as a system component is actually a set of natural and artificially prepared objects, which fall between each other in various interactions. Each of the system components affects other elements in a specific manner. The human controls the technical object that performs operational work in a specific environment. The environment and the object influence humans by defining for them certain input states. The human affects the object assuming certain output states. Similarly, there can be described other interactions of the environment and the object. One of elements that should be taken into consideration is sociotechnical subsystem that includes human and technical objects.

The interaction of individual components to other elements of the system depends on both the input states and on the ability of the system to space-stated transformation of input states to the outputs.

In the present three-stated model, the elements states express the following: 1 – the correct operation, 0 – no operation, and 2 – incorrect operation. Therefore, for their determination, there is only a need to use three values: 0, 1, and 2. If the item has only one input and one output, the current status of its input is expressed by the vector size $\boldsymbol{X}$, and the current state of its output is expressed by the vector value $\boldsymbol{Y}$. Following this, the element gets some input action that is specified by the X value, and the output action is specified by the Y value.

A sociotechnical subsystem (the human – the technical object) has an assigned ability for the satisfactory processing (transferring) of energy and information. If a set of characteristics of the sociotechnical subsystem condition meets the requirements of efficient and safe operation, then a transformation rate W obtains a nominal value of $W = 1$. If a set of characteristics of the sociotechnical subsystem potential downstate condition is at the limit of meeting the possibilities of safety requirements, then a transformation rate W obtains a nominal value of $W = 2$. Finally, if a set of characteristics of the sociotechnical subsystem downstate condition does not meet the requirements, we can observe the consequences listed below.

Incorrect transformation occurs when the indicator describing the ability of sociotechnical subsystem for the processing (transferring) of energy and/or information takes the value $W = 1$. In the opposite case, there is a failure and the index assumes the value $W = 0$, when the object did not indicate the ability to achieve flows processing (transmission). The value $W = 2$ is assumed if the object incorrectly processes (transmits) the energy and information.

Thus, to determine the ability of the element to operate, the three numbers 0, 1, and 2 will also be used. Conversion of $\boldsymbol{X}$ input to the $\boldsymbol{Y}$ output while taking into account the particular value of transformation rate W is shown in Fig. 2.

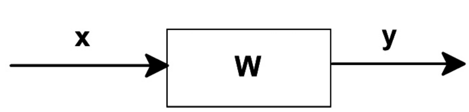


Fig. 2. Block diagram of system's component

Following this, we can stated that

$$X \wedge W = Y, \text{ and } X, Y, W = 0,1,2 \tag{1}$$

where

X – input (magnitude describing the external influence on the element),

Y – output (magnitude describing the influence of the given element on the other elements and environment),

W – object efficiency (magnitude describing the transformation level),

$\wedge$ – a sign of conjunction.

From Equation (1), it follows that if the object is in upstate, then $W = 1$, the inputs and outputs can take the desired states. If the object is in potential downstate, then $W = 2$, thus maintaining the safety criteria. This is regardless of the status of inputs, and outputs are consistent with the state of the object. Therefore, they are always incorrect. If the state of the object, $W = 0$, does not allow one to make any transformation performance, then its outputs are always equal to zero. In other words, the element does not respond to any influence.

Elements of the system are mutually coupled. They can interact with other elements, including the human and environmental ones. Only in this way does the relevant element takes defined output states of other elements through their inputs. Hence, the output states are transformed into the same states of the inputs of coupled elements.

An example would be the operation of signalling at the crossroads of communication that displays three colours: green, when $W = 1$, driving is safe; red, when $W = 0$, driving is not safe; and yellow, when $W = 2$, driving is temporarily not safe or not dangerous. If we do not know the past states of the signalling and consider the process without memory, we decide that the situation is uncertain. Thus, we are careful at the yellow signal, and driving is unacceptable due to a potential collision threat.

2. Transportation system – analysis of unsafe events performance

Based on the developed model, it is possible to conduct safety risk analysis for a selected type of the sociotechnical system – a transport system.

Following [3], a transport system is defined as *a socio-technical system that consists of a cluster of aligned elements: artefacts, knowledge, markets, regulation, cultural meaning, infrastructure, maintenance networks, supply networks, etc*. As a large sociotechnical system, it provides transport services by employing a variety of technologies and solutions. Thus, there can be identified various interactions between technological, social, economic, political, legal and environmental dimensions. These interactions affect the safety of transportation system. Following this, there is given a comprehensive safety risk analysis of the large sociotechnical system in order to provide a formal hazard event occurrence probabilities definition.

Let us examine the consequences posed by an adverse (unwanted) change of the "Human – Technical object – Environment" system's elements state. It is clear that, when the technical and/or social requirements of sociotechnical system are not met, it can interact in unpredictable ways, and then the whole system is in a hazard state.

Moreover, assume that a human (the decision-maker, operator) can be in the following states: 1 – efficiency, 2 – a potential inefficiency, or 0 – inefficiency (disability). For the object (mechatronic means of transport), there can be defined the states of 1 – upstate, 2 – potential downstate, and 0 – downstate. The last element – the environment (natural environment and technosphere) – may be in the states of 1 – sufficiency (and/or non-truculence), 2 – the potential inadequacy (and/or unpredictable truculence), or 0 – complete inadequacy (and/or non-truculence).

The above-mentioned states have specific causes. It is known that the causes of incorrect operation of system components may result in the operator's psychophysical state change and partial failure of the facility and disturbances in the environment. A pause in operation (interaction) of system components may result from injuries suffered by a human, technical object failure, or environment inactivity.

Whenever we talk about improper influence or the lack of action between and in system elements, we must take into account the occurred in reality cause and effect mechanisms. Following this, the main definition should be introduced.

The *hazard* is defined as a situation (the system state), wherein at least one of the elements is characterized by an undesirable state, and thus can be harmful to other components of the system.

Thus, we can talk about the hazards of different types (small and large), depending on system elements' current states and the number of elements that are in undesirable states. Thus, the *hazard measure* is given as a probability of the system being in the undesirable condition, consisting in that at least one of the elements threatens to other elements. Moreover, the *active safety* of a system is meant as a situation in which all the elements work correctly, and the *passive safety* – a situation where none of the elements perform at all (no operation).

The hazard results from specific causes leading elements into undesirable states. These causes may include, e.g., injuries suffered by the operator, the failure or destruction of technical facilities, degradation, or the disturbance of the environment. Undesirable changes in system element states are inevitable, but the risk of their occurrence can be changed, if we use specific preventive and proactive strategies (e.g., preventive maintenance and repairs, inspections).

Being aware of the adverse consequences of faulty interactions, a variety of initiatives designed to protect the system components against the effects of incorrect operation are used. For this purpose, the technical facilities are suitably equipped in order to increase their resilience to external impacts. Features of such objects are called *passive safety*.

Taking a step further, technical facilities should be equipped with subsystems enabling the performance of safe work processes, as well as subsystems to prevent the possibilities of conflict and failure occurrence. Features of such objects are called as *active safety*.

In the specified conditions, one can also refer to the concepts of passive and active safety for operator and environment performance. Thus, the values considered in the model can also represent (occurring in reality) various forcing factors. Therefore, analysis and assessment of the occurrences of hazard events in a technosphere are presented below.

Among the different situations (states) of the human – object – environment system, there may be many unsafe situations. An safety risk measure may be defined as a probability $q_K(K=1,2,...)$ of a particular combination of unwanted (internal) system's element states occurrence, given as the following:

$$\begin{cases} q_1 = P\{(W_1 = 0) \wedge (W_2 = 1) \wedge (W_3 = 1)\} \\ q_2 = P\{(W_1 = 1) \wedge (W_2 = 2) \wedge (W_3 = 1)\} \\ \quad \ldots \\ q_N = P\{(W_1 = 0) \wedge (W_2 = 0) \wedge (W_3 = 0)\} \end{cases} \quad (2)$$

Therefore, one can understand the expected possibility of a critical change of sociotechnical subsystem's elements state using a hazard term. Changes take place under the influence of mutual, failure-inducing components interactions. Thus, the hazard measure may be defined as a conditional probability Z_i, $(i = 1, 2, 3)$ of such an event occurrence, and may be given as follows:

$$Z_i = P\{(W_i(t + \Delta t) = 0) \big| (W_{j \neq i}(t) = 0)\} \quad (3)$$

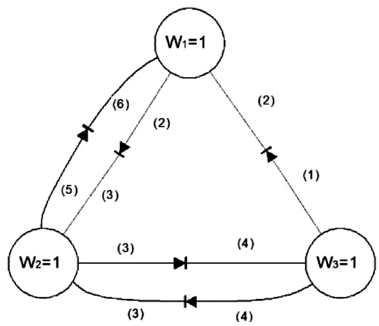
where

W_i – the expected state of the unsafe element,

$W_{j \neq i}$ – the current state of the element being unsafe for other elements.

Let us consider the example of four situations occurring in the system. One safe and three out of 25 considered unsafe situations that take into consideration the operator, object, and environment states.

First, the safe situation of the first type is analysed (Fig. 3). An efficient operator receives a valid message given by the relevant environment. He delivers the correct impulses being received correctly by the properly operated object. All further system's elements interactions are correct. It should be noted that the safe situation of the second type could occur, i.e. if none of the elements are working. As it can be seen in the Fig. 3, the numbers in parentheses indicate the sequence of interactions.



Legend:
Information flows (steering ones): 1-2, 2-3, 5-6; energy flows (operational): 3-4, 4-3; W_1 – human (operator) mental capacity, W_2 – energy efficiency of mean of transport, W_3 – environment accuracy

Fig. 3. The safety situation in the "Human – Object – Environment" system

An unsafe situation of the first type is presented in Fig. 4. This situation is caused by the disability of operator. An inefficient operator, despite receiving a valid message given by the friendly environment, cannot properly control the operational object performance. Thus, all the other interactions of the system components can be improper and hazardous.

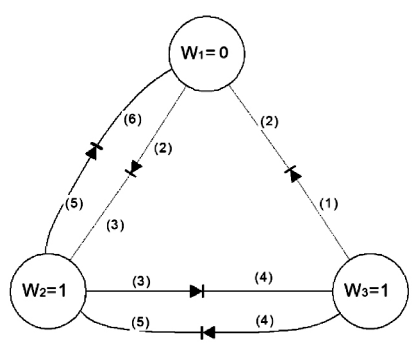


Fig. 4. Potentially unsafe situation in the system due to a potential disability of the operator (the numbers in parentheses show a virtual sequence of interactions and feedbacks)

The entire system is unsafe, because the operator is unable to perform satisfactorily. A measure of this hazard event occurrence is the probability $q_1 = P(W_1{=}0, W_2{=}1, W_3{=}1)$. In the given situation, there may occur specific hazards described by conditional probabilities as follows:

$$\begin{cases} z_2 = P\{(W_2 \to 0)|(y_{32} = 0)\} \\ z_3 = P\{(W_3 \to 0)|(y_{23} = 0)\} \end{cases} \tag{4}$$

and considered in the order of their possible occurrence.

An unsafe situation of the second type is presented in Fig. 5. This situation is caused by a downstate of the object.

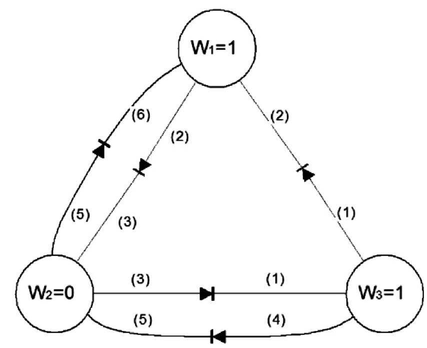


Fig. 5. Potentially unsafe situation in the system because of the potential downstate of the object (the numbers in parentheses show a virtual sequence of interactions and feedbacks)

According to the Fig. 5, an efficient operator receives a valid message given by the relevant, friendly environment. Properly interacting, he delivers the correct impulses being not received by the unusable object. All further interactions between elements will be incorrect (as in the previous situation) and can be unsafe.

The entire system is unsafe because the technical object is inoperable. A measure of this hazard event occurrence is the probability

$$q_2 = P(W_1{=}1,\ W_2{=}0,\ W_3{=}1).$$

In the given situation, there may occur specific hazards described by conditional probabilities given by the following equations:

$$\begin{cases} z_1 = P\{(W_1 \to 0)|(y_{21} = 0)\} \\ z_3 = P\{(W_3 \to 0)|(y_{23} = 0)\} \end{cases} \tag{5}$$

An unsafe situation of the third type is presented in Fig. 6. This situation is caused by an inappropriate reaction of the environment. The described above situation may develop in the same way as the other kinds of unsafe situations, until there begins the improper influence of the environment even despite proper performance of the object. Moreover, as in the unsafe situation of the second type, all interactions of the system elements are inappropriate and can be hazardous.

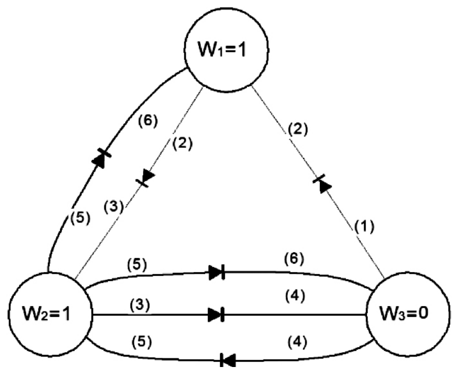


Fig. 6. The hazardous situation in the system because of the undesirable reaction of the environment (the numbers in parentheses show a virtual sequence of interactions and feedbacks)

The entire system is unsafe because the environment is reactive. A measure of this hazard event occurrence is the probability

$$q_3 = P(W_1=1,\ W_2=1,\ W_3=0).$$

In the given situation, a specific hazard described by conditional probabilities given by equations may occur as follows:

$$\begin{cases} z_1 = P\{(W_1 \to 0)|(y_{21} = 0)\} \\ z_2 = P\{(W_2 \to 0)|(y_{32} = 0)\} \end{cases} \tag{6}$$

The above examples serve to illustrate the primary analysis of unsafe events occurrence in the system "operator – technical object – environment." The advantages of this kind of approach to the sociotechnical systems safety issues and critical hazard events occurrence seem to be obvious. However, there are some difficulties related to the estimation of the previously described hazard measures. Namely, the determination of the hazard probability should be done for each situation separately, since the states of the elements of the system are dependent.

Synthesis of the obtained results should enable one to define system safety/safety risk as a function of time. The data obtained can also be used to build a simulator that allows one to investigate the current model.

Conclusions

The presented model can be helpful in the analysis of unsafe situations in transport systems but also in other large sociotechnical systems.

Of particular importance are the relationships between the main characteristics of the "human – technical object – environment" system, being analysed, e.g., in works [8, 33, 34]. Dependability determines safety and efficiency, durability maintains dependability, safety, and effectiveness, while the so-called appropriateness provides positive results of all of the mentioned system characteristics. This study focuses on safety issues and is a contribution to the continuous improvement of the methods for the analysis and evaluation of socio-technical system performance in variable operating conditions.

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