17
Virtual Working Environment

Teodor Winkler, Jaroslaw Tokarczyk, and Dariusz Michalak

17.1
Methodological Assumptions

CoVan (1995) gave the following definition of *safety*: the relative acceptability of an operation in terms of losses or risks. The term *loss* means degradation of a system or components. That notion includes damage to health or loss of life of the worker and destruction material structures. An obvious place where such loss can take place is the work environment.

With the development of efficient tools for computer modeling, it was possible to recreate the real working environment in the virtual world. Since then, shaping of the working environment and prevention of losses is realized through what affects the working conditions and work safety. The methods that affect work safety in real working environments and also those which permit the transfer of the real working environment to the virtual state have been developed to a great extent. Both of these approaches complement each other. The real working environment is a source of knowledge about safety, and the virtual working environment is an area where knowledge resources are organized, collected, and disseminated. The result is that a joint, methodological, and consistent approach to shaping safety and prevention of losses in all stages of technical means used by people in the working environment has been formed. Figure 17.1 illustrates this problem. Numerous detailed engineering methods supporting prevention of losses, both material losses and those resulting in damage to health, including death, were attributed to each phase of the technical mean life-cycle. This is not the only or the main purpose of these methods. Methods grouped in the design phase under the common name *virtual prototyping* are first of all intended for verification of design features of technical means. This is in the light of technical criteria (functional and strength criteria), which in the case of not meeting them can cause destruction or impairment of technical means or their components. Verification of design solutions regarding ergonomic or biomechanical criteria prevents loss of health and life. Examples of relationships among the methods used in both research streams will also be presented.

Handbook of Loss Prevention Engineering, First Edition. Edited by J. M. Haight.

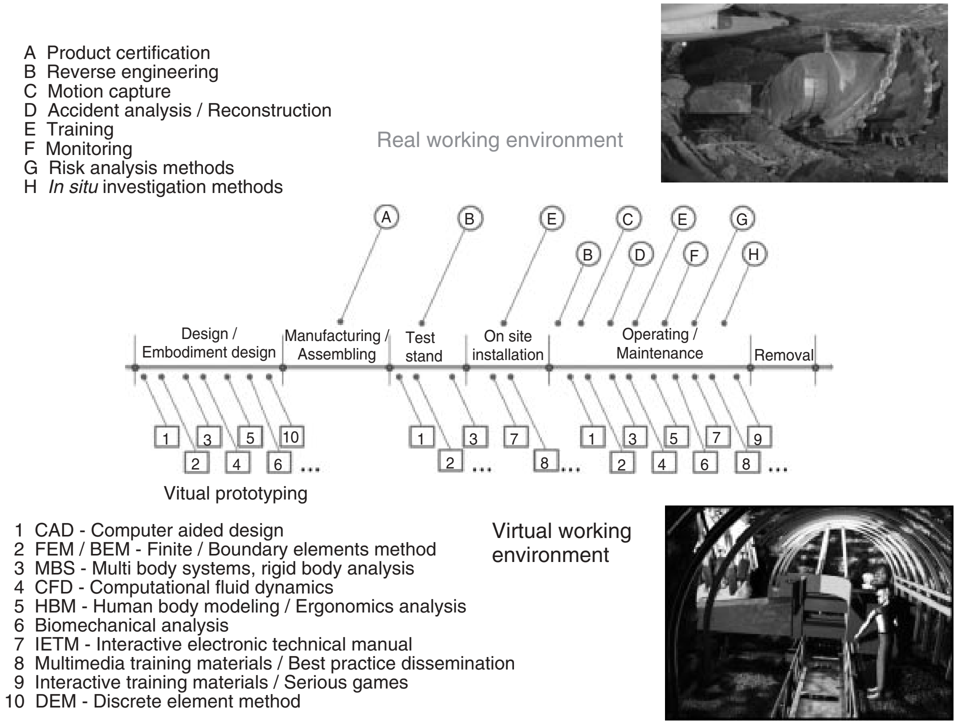


Figure 17.1 Engineering methods and measures supporting loss prevention during the life-cycle of technical means.

17.2
Elements of the Virtual Working Environment Structure

For a description of elements of the virtual working environment, we start from the notion of an *anthropotechnical system*. In Figure 17.2a, a generalized diagram of an anthropotechnical system is presented. The relationships between a man and the technical aspects of an anthropotechnical system are marked on the diagram, namely somatic relationships and receptor relationships.

Somatic relationships describe spatial relationships between artificial objects and the human body. They result directly from human carnality and were formulated as follows (Winkler, Dzieniakowski, and Jaworski, 2003; Winkler, Michalak, and Bojara, 2004):

- limitations imposed on the space occupied by the human body
- range of limbs
- forces exerted by the limbs
- postures taken during manual jobs
- loads on the musculoskeletal system.

Somatic relationships are realized by the human locomotive system.

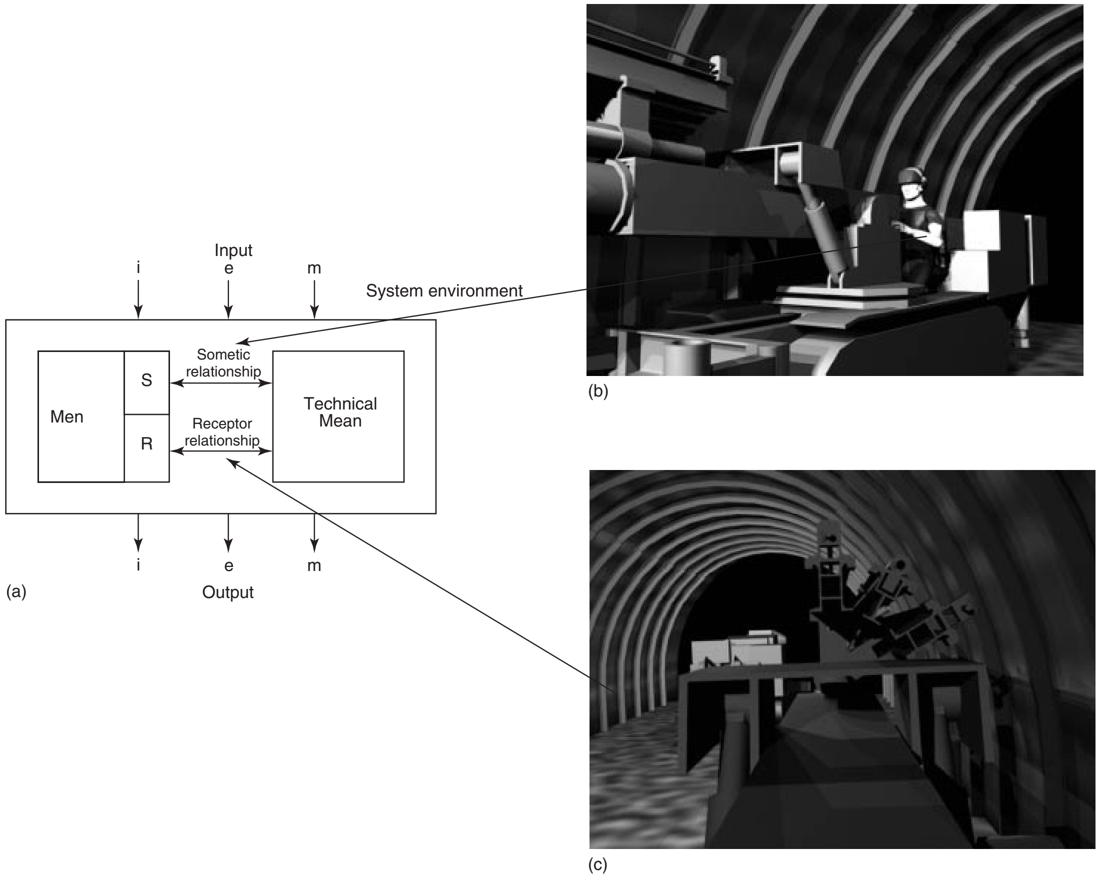


Figure 17.2 Generalized diagram of anthropotechnical system (a), somatic relationships (b), and receptor relationships (c).

In *receptor relationships*, the following receptors are involved: visual receptor, hearing receptor, olfactory receptor, and tactile receptor. Both somatic and receptor relationships connecting the operator with the road header are illustrated in Figure 17.2b and c, respectively.

Improperly formed relationships can cause degradation of the anthropotechnical system and can lead to losses in terms of health and human life.

Anthropotechnical systems are part of a larger system, which is the entire *working environment*. It also includes processes and phenomena that occur in certain *surroundings*. In the environment, *hazards* (natural or technical) can occur. Natural hazards appear most frequently in mining, for example, bumping, methane explosions, harmful airborne dust, outbursts of rocks and gases, endogenous fires, and mine water.

Technical hazards are caused by improper operation of technical means, for example, collision, loss of stability, and loss of structural bearing capacity, resulting in overloads.

The adverse impact of natural and technical hazards on human health is classified as a health hazard (Cornelius and Turin, 1997; Gallagher, Landen, and Fotta, 1997; Gallagher, 2006; Mayton *et al.*, 2010). These hazards manifest themselves in the adverse effect on the respiratory system (e.g., airborne dust), hearing (noise), musculoskeletal system (e.g., vibration), cardiovascular system (e.g., mine water radiation), and so on. Improperly formed somatic and receptor relationships also contribute to the appearance of health hazards, for example, within the musculoskeletal system as a result of awkward postures during work, or through exposure of the skin to hot surfaces.

The virtual working environment is a computer representation of selected features of:

- real material objects (natural and artificial)
- people
- processes
- phenomena
- hazards.

These representations take the form of computer models, animations, and simulations. The structure of the virtual working environment is given in Figure 17.3 in the form of a shell model. Four shells inside the model image form the core of the virtual working environment. These are the computer models of geometric and anthropotechnical features, animations, and simulations of processes, phenomena, and hazards. The shell of special software supporting the creation of computer models, animations, and simulations is adjacent to those four shells.

The virtual working environment is complex and non-homogeneous regarding the models used. This is what reflects differentiated requirements of specialists (users) that shape safe working conditions. Specific *windows* covering the parts of the virtual working environment refer to worker safety and health protection considered by these specialists. The content of each window is made available by "*viewports*," supported by *information and communication technologies* (ICT) and by

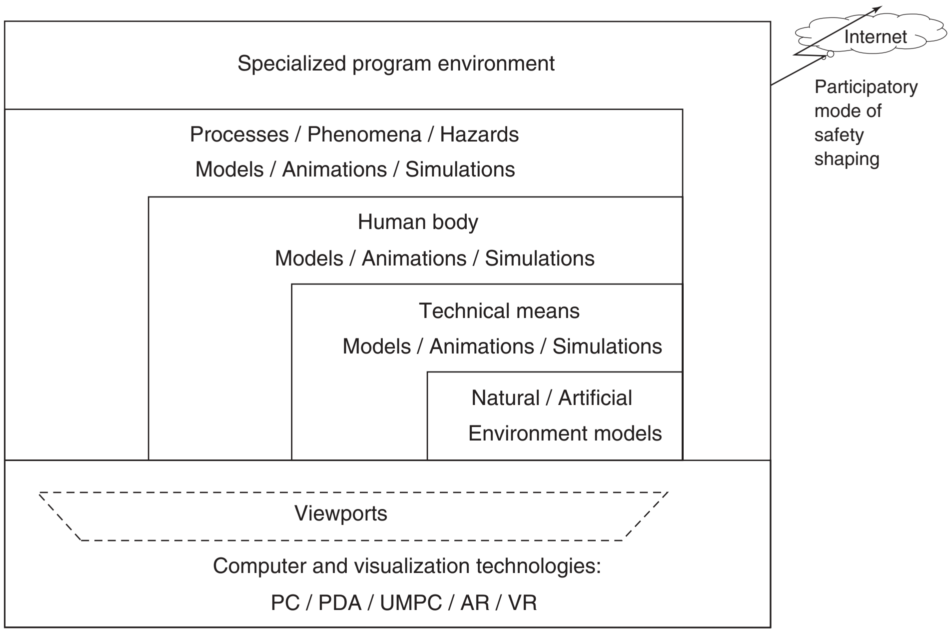


Figure 17.3 Structure of virtual working environment.

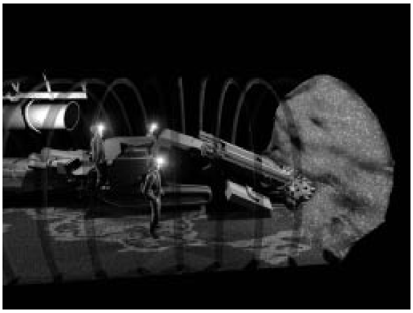
computer hardware. For example, simulation of the safe dismantling of a mining machine can be available in the form of an *interactive electronic technical manual* (IETM) on an Internet platform on a PC. It can be delivered directly to the mechanic working on the dismantling by a *personal device assistant* (PDA) computer (Winkler *et al.*, 2007; Winkler and Schmid, 2008). It can also be displayed during training on the background of the real machine using augmented *reality* technology. Such a structure of a virtual environment is close to the idea of graphical kernel system which became the basis of the present-day computer-aided design (CAD) systems (Enderle, Kansy, and Pfaff, 1984).

A group of specialists (users) who shape safe work conditions are scattered geographically and they represent different branches or parts of the organization. Due to the *participatory design mode* method (Määttä, 2003), it is possible to gain access to the virtual working environment on the Internet platform. Such a form of virtual shaping of the working environment can be called the p*articipatory mode of safety shaping*, and this allows all participants to engage in the design.

The virtual working environment shown in Figure 17.4a contains features described above. In the natural environment of an underground mine, the *process* of roadway excavation is realized. An *anthropotechnical system* is represented by models of the human body, machines, support structures, and equipment. Figure 17.4b illustrates the initial phase of a rock outburst and a gas *phenomenon*.

The following sections present methods and tools supporting the creation of a virtual working environment. By introducing a virtual working environment to the

(a)



(b)

Figure 17.4 Mining virtual working environment in the working state (a) and in an emergency state (b).

design practice, it is possible to identify and evaluate hazards that can occur in a real working environment in the early phases of the design of technical means and processes.

17.3 Engineering Approach to Loss Prevention Within the Life-Cycle of Technical Means

Intentional use of *engineering methods* in the assessment of technical means in all *stages of their life-cycle* is the essence of an engineering approach to loss prevention. Several methods are used in engineering practice, namely:

- geometric modeling
- finite element method (FEM)
- multibody system
- computational fluid dynamics (CFD)
- human body modeling.

Current engineering methods use *models*, that is, sets of intentionally selected features describing objects, processes, and phenomena, including complex anthropotechnical systems to a great extent.

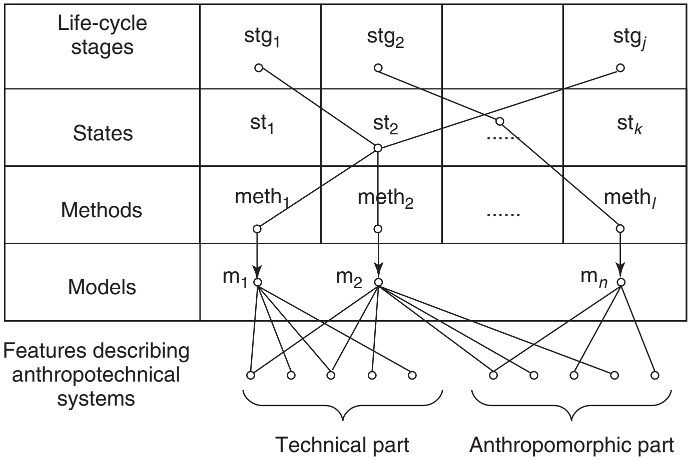


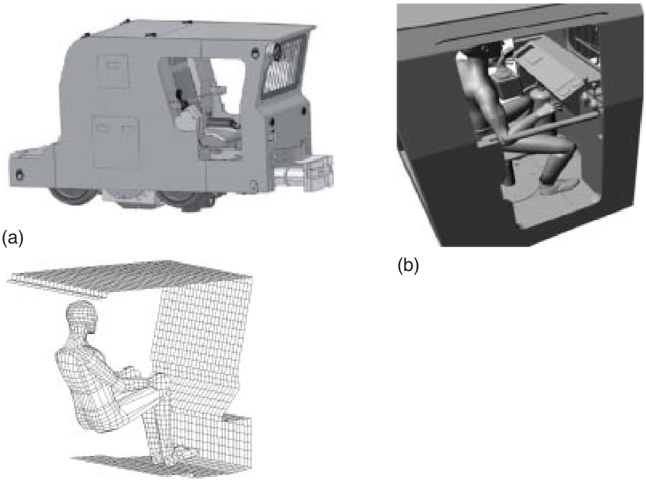
Figure 17.5 Creation of adequate models of anthropotechnical systems.

Let us assume that the complex anthropotechnical system in a selected stage of its life-cycle is the subject of assessment. These systems can be in one of operational states or in one of emergency states. For the purpose of assessment, the specified method should be selected in the light of the chosen system of criteria. The creation of adequate models of anthropotechnical system is described in Figure 17.5. The following symbols were adopted:

- ($stg_1 \ldots stg_j$) for life-cycle stages
- ($st_1 \ldots st_k$) for states, operational or emergency
- ($meth_1 \ldots meth_l$) for applied methods.

An appropriate model consists of features distinguished from the set of features describing anthropomorphic and technical parts of the anthropotechnical system. Several models ($m_1 \ldots m_n$) can be created for one anthropotechnical system (Winkler and Tokarczyk, 2011).

In the design stage of a railway locomotive used in underground transportation in hard coal mines, working and emergency states are taken into account. All geometric features of the machine described by means of the geometric modeling method are presented in Figure 17.6a (MINTOS, 2007). For an analysis of the range of an operator’s limbs and field of view, a human body modeling method is used. The geometric model comprises features indispensable for carrying out an extensive ergonomic analysis or assessment of the arrangement of control components (a cognitive engineering assessment) (Figure 17.6b). For assessment of the results of emergency braking, a reduced set of geometric features was modeled. For analysis of the behavior of the human body represented by an articulated total body (ATB) model, the multi-body analysis method together with FEM are used (Figure 17.6c).



(a) (b) (c)

Figure 17.6 Selected features of the railway locomotive (a) for ergonomics (b) and safety (c) analysis.

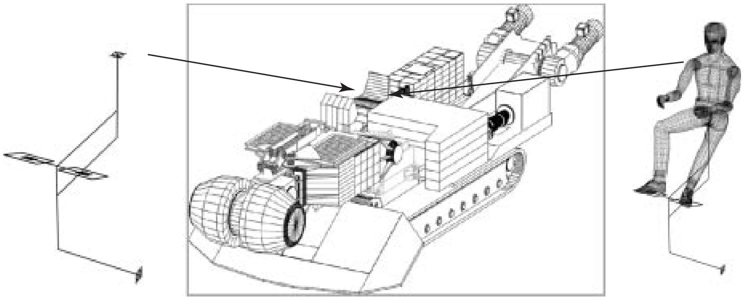
Methods and tools used for the creation of elements of the virtual work environment, which aids engineering methods eliminating losses in other stages of the life-cycle of technical means, are described in the following.

17.4 Methods and Tools Supporting the Creation of Elements of a Virtual Working Environment

17.4.1 Computer-Aided Design (CAD)-Based Modeling

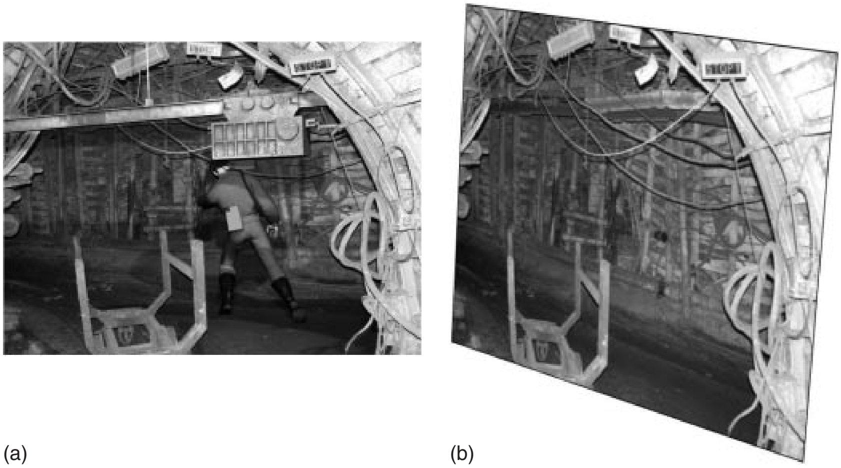
The easiest way to create a virtual working environment is to use the simple combination of both the CAD and human body models in a common software environment. In the early stages of design, the geometric features are defined but not quite precisely enough. In such cases, drawings and models with a reduced amount of detail are used. In Figure 17.7a, a simplified model of the operator's seat in a mining machine, a roadheader, is presented. The model comprises features sufficient to fix the seat position on the machine body (Figure 17.7b), in order to ensure the operator's proper field of vision, presented in Figure 17.7c.

A lack of data required for creation of the model often occurs during reconstruction of accidents in the operating stage of the life-cycle. Then, to recreate a view of the objects that are involved in the accident, simplified geometric models and photographs were used. The miner at the moment of collision with the braking unit of the suspended monorail is shown in Figure 17.8a. The simplified model



(a) (b) (c)

Figure 17.7 Proper positioning of the simplified seat model (a) on the machine body (b) affects the field of vision (c).



(a) (b)

Figure 17.8 Reconstruction of the accident place (a) using photographs of the road junction (b).

of the road junction covered with photographs (Figure 17.8b) is completed by the geometric model of the braking unit and the human body model. The photographs do not reflect precisely the geometric relationships, but they can also be used in reverse engineering methods, based on photogrammetry, to recreate damaged structures (Winkler *et al.*, 2008). A very efficient and accurate method of reconstruction of existing structures is the 3D laser scanning method (Gregor *et al.*, 2008). Transformation of the existing production systems into its exact 3D digital copy can be used for complex safety analyses of the layout of production means or the layout of transportation routes. In the ''Stuttgart Enterprise Model'' project, the virtual environment is a part of digital factories and it is used as a tool aiding the planning of new factories (Hummel and Westkämper, 2006).

The variability of geometric features of material objects is described by *parametric models*. In the field of machine construction, these models present both the

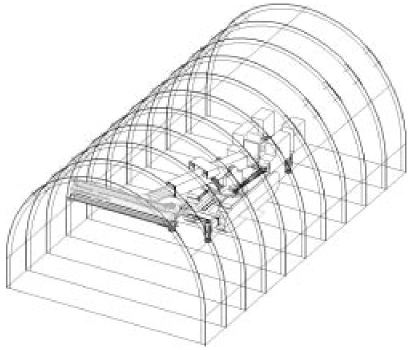


Figure 17.9 Self-propelled mining machine: a roof bolter.

changeability of the geometric form of single components and the changeability of the arrangement of assemblies. This allows the development of machines and equipment. In the case of self-propelled machines operating on uneven or inclined ground, an unfavorable arrangement of the machine assemblies can lead to loss of stability. A self-propelled mining machine, a roof bolter, is presented in Figure 17.9. A model of the machine consists of solid models of assemblies, where each has its own center of gravity with a certain mass assigned to it. The center of gravity of the whole machine depends on the momentary position of moveable assemblies.

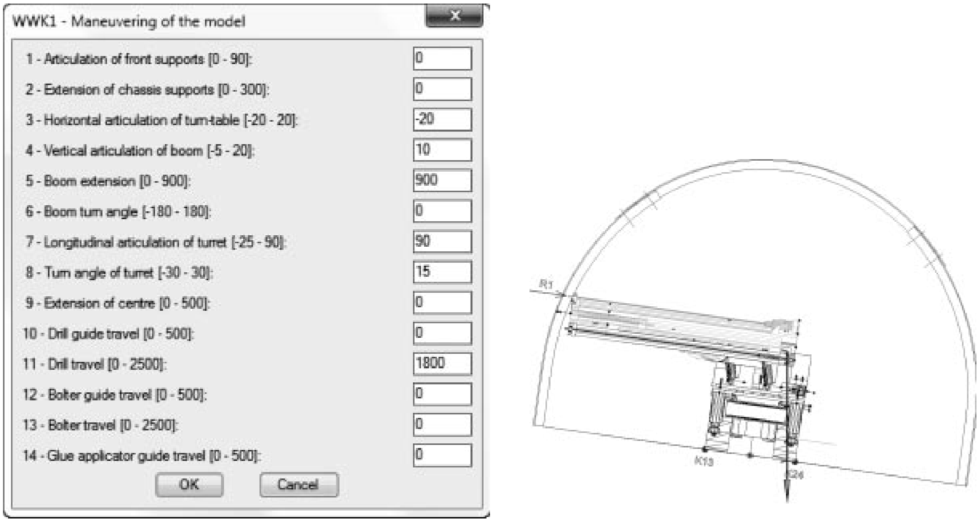
An analyzed machine realizes 18 operational movements and the creation of models for each movement by means of standard CAD commands, which would be time consuming. Hence a computer program modeling kinematic chains of roof bolters was developed. Therefore, the position of the assemblies and their centers of gravity are defined (Dudek *et al.*, 2003). A dialog box with the parameters describing operational movement is shown in Figure 17.10a. The position of the roof bolter assemblies while operating on transversal inclined ground is presented in Figure 17.10b.

17.5 Human Body Modeling

Methods of human body modeling together with CAD-based modeling methods are the basis for virtual prototyping of the anthropomorphic part of complex anthropotechnical systems. It is not possible to recreate in detailed complexity the human body structure by using only one type of model. Hence many concepts of human body models appear, each focusing on specified aspects of the human body structure.

There are two main families of human body models:

- Full-scale anthropomorphic test devices that simulate the dimensions, weight proportions, and articulation of the human body, which are usually used to analyze the dynamic behavior of the anthropomorphic test device in simulated



(a) (b)

Figure 17.10 Parametric model of the roof bolter: parameters describing operational movements (a) and coresponding assemblies arrangement (b).

vehicle impacts. They are also called dummies, anthropomorphic test dummies (ATDs), or mannequins
- Computer models which represent the anthropometric features of the human body.

Both physical and digital models are complementary and contribute to loss prevention.

The precision of the reconstruction of the human body structure with the use of material or computer models is expressed by an idea of ''biofidelity'' (von Merten *et al.*, 2008). Factors affecting the biofidelity of human body models are given in Table 17.1.

The scheme in Figure 17.11 illustrates how these factors contribute to the biofidelity of human body models. Systematic association of factors leads to characteristic program groups. These are described in more detail in the following sections.

17.6
Anthropomorphic Test Dummies

ATDs are used for the extensive analysis of the behavior of the human body segments in impacts caused by dynamic phenomena during stand tests. In the automotive industry, data such as velocity of impact, bending, folding, and torque and decelerations of body during crash tests are recorded. The ATDs were originally developed for automotive impact analysis, but they are also used for the evaluation of most kinds of impacts. In the aviation industry, drop tests were conducted utilizing

Table 17.1 Factors affecting the biofidelity of human body models.

Modeling scope	Modeling method	Graphical representation	Represented states
Anthropometric features (1)	Geometric modeling (3D modeling) (1)	Sticks (1)	Operational state (1)
Musculoskeletal system (2)	Finite elements method (2)	2D surface elements (e.g., facets) (2)	Emergency state (2)
Inner organs (3)	Multi-body system (3)	3D objects (3)	
Kinematic chains (4)	Biomechanical analysis (4)		
Loads in musculoskeletal system (5)			
ATD features (6)			

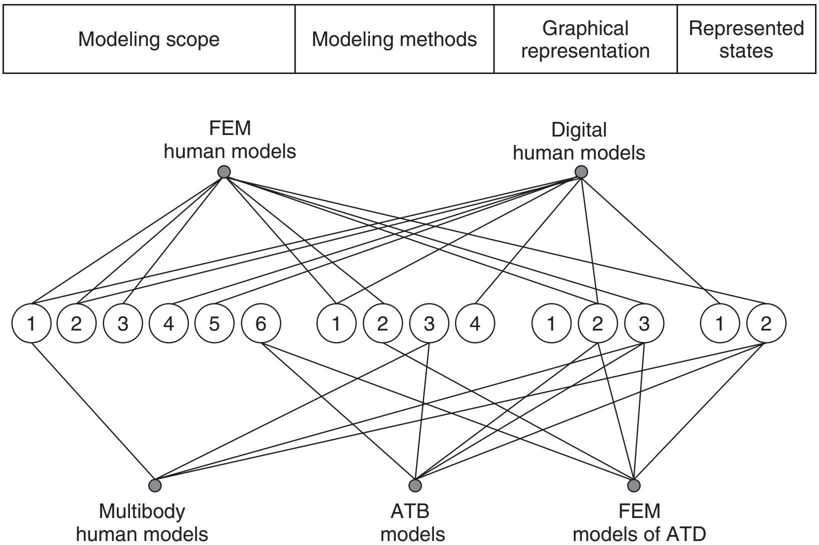


Figure 17.11 Grouping factors affecting the biofidelity of human body models.

military impact conditions for helicopter seat certification (Manning and Happee, 1998). Hybrid III is the dummy most widely used in frontal crash testing. In order to produce a biofidelic dummy, a variety of materials are used; for example, steel and aluminum imitate load-bearing elements of the skeletal system, and foam and vinyl are used for the modeling of soft tissues (Kan, Marzougui, and Bedewi, 2003).

The outer structure of the Hybrid III dummy is shown in Figure 17.12a. The model segments are connected with each other with joints. Figure 17.12b, illustrating the torso segment with its components, exemplifies the complexity of dummies (see *http://www.humaneticsatd.com/crash-test-dummies*). Thanks to the broad variety of material properties, dummies behave at the test sleds like human body segments during a real crash. The new generations of advanced dummy solutions have extended design and measurement capabilities. Instruments for the measurement of axial, angular, and shear displacements and also tensions and deflections are embedded in the dummy components (Haffner *et al.*, 2001). Dummies have become a standard in crash tests not only in the automotive industry, and they are available in many sizes (5th, 50th, 95th percentiles), representing women, men, and children being drivers, pilots, passengers, and pedestrians. They allow for the recreation of frontal, rear, side, and oblique impacts and human response to mechanical forces within public transport, automotive, aviation, aerospace, and military situations (see *http://www.humaneticsatd.com*). For a better understanding of the percentile measures used in anthropometry, a brief explanation is given below.

A percentile is a value of a variable which determines the percentage of, for example, people population which is located below this value (NIST/SEMATECH, 2012). Percentile divides the population or set of units into 100 equal parts. For example, the 95th percentile value means that 95% of the population is below this value and 5% is above this value. Absolute values of the measured variables depend on the time and place of investigations. Regarding the human body height, Polish 5th percentile women are 1502 mm tall and Polish men 1600 mm (Gedliczka, 2001). This means that 5% of the measured population falls below these values. It correlates with our intuitive understanding of categories "low" and "high." So, the 5th percentile person is considered to be low, because only 5% of the population

(a)

(b)

Figure 17.12 Full assembly of the hybrid III 50th male dummy (a) and upper torso assembly (b). (Reproduced with permission of Humanetics Innovative Solutions, Inc.)

is shorter. On the other hand, a 95th percentile person is considered to be high, because as many as 95% of the population are lower.

Test stands for crash tests and preparation of tests are time consuming and expensive. The use of computer models is a complementary process to physical testing. Dummy models can reduce the number of tests required and thus reduce time and cost. They can be used for the planning of tests and after sufficient validation they may be used for the prediction of human body behavior under dynamic conditions and for safety evaluation.

17.7 Multi-Body Models of ATDs

The *ATB model* is a *multi-body model* directly brought out from the Hybrid III dummy (Ding *et al.*, 2011). The structure of the dummy is mapped by 15 rigid ellipsoids, which are connected by 15 or 17 rigid body joints (Figure 17.13). Geometric measures, mass, and mechanical properties of the manikin segments were measured and converted to the specific input format requirements for ATB model. A standing and seating Hybrid III dummy were measured. Each ellipsoid is described by external measures of the represented dummy segment. The measured

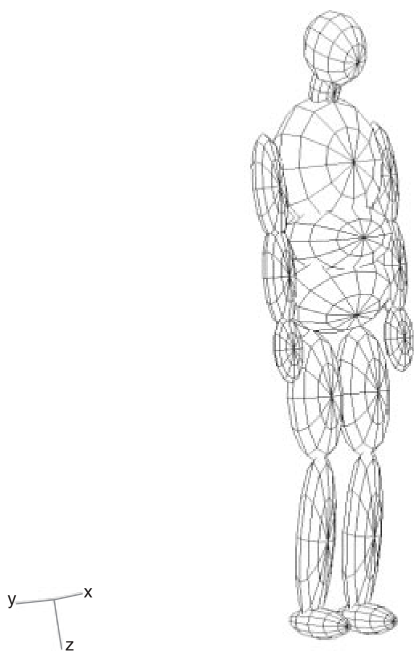


Figure 17.13 Structure of the ATB model.

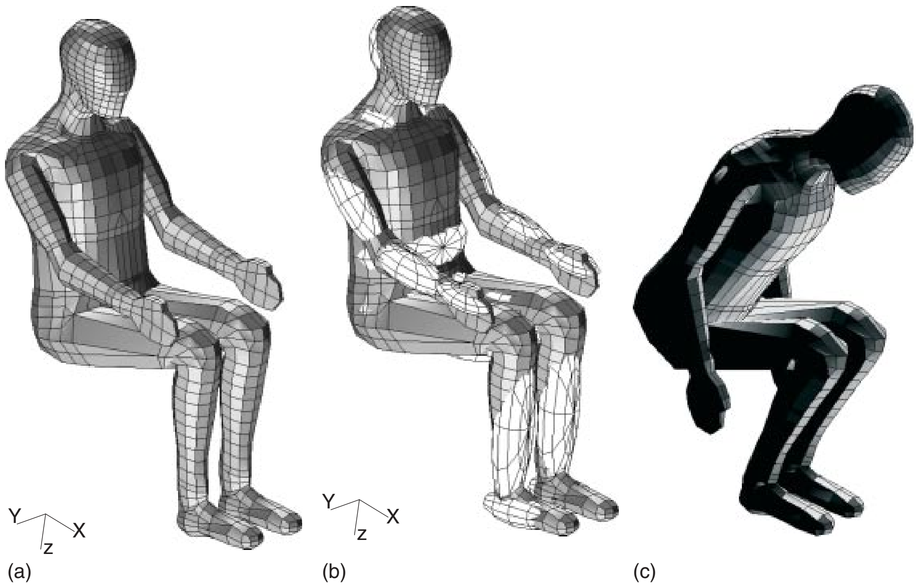


Figure 17.14 Surface model (a) covers multi-body segments of the ATB model (b) and the segments motion can be analysed (c).

segment mass, segment center of gravity location, and segment inertia are assigned to each ellipsoid. The joint resistance torque, as a function of joint rotation angle, is also designated for each joint. Demonstration simulations using the Crash Victim Simulation (CVS)/ATB model were performed and the results were compared with data resulting in physically realistic simulations (Kaleps *et al.*, 1988). Based on data resulting from measurement procedures, completed by data sets from anthropometric surveys, an interactive program called Generator of Body Data (GEBOD) was developed (Cheng *et al.*, 1994). The GEBOD program automatically generates data sets for human and dummy rigid body dynamics modeling. The model behavior, that is, trajectories of the ATB model segments, are simulated by the CVS program. The occupant–environment interaction is analyzed in order to detect contacts. Depending on the range of the analysis, ATB models are implemented in some FEM programs (MSC Software, 2010). ATB rigid segments coated with FEM entities are shown in Figure 17.14a. In Figure 17.4b a *surface model* consisting of shell elements spread on the grid resulting from the digitization of the dummy manikin is presented. The surface model attached to the ATB model segments and covering them retain a realistic shape during the motion of the segments (Figure 17.14c). Hence, for example, the occupant–belt interaction can be analyzed (MSC Software, 2010).

17.8
Multi-Body Human Models

Commonly used in the practice of transport safety shaping are multi-body human models developed by TNO Automotive Safety Solutions (TASS). The outer shape of the model is coated by facet surfaces, which adhere to rigid and flexible bodies. These facets are FE contact elements with defined stress-based contact characteristics. Soft tissue deformation results from the facet–facet contact interactions and from facet–environment interactions (Figure 17.15) (Meijer *et al.*, 2012).

Recently, an active human model was developed by TNO (Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek or Netherlands Organization for Applied Scientific Research) in the software MADYMO. The model was developed in order to predict human behavior in the pre-crash and crash phases in one simulation for various loading conditions. The model can be used for both pedestrian and occupant impacts. This model was based on earlier human models developed in MADYMO (MADYMO, 2011). Various active components were added. The active behavior of the model is posture maintenance only, Figure 17.16 (Meijer *et al.*, 2012).

The model has been validated for frontal, lateral, rear, and vertical loading directions and also for high-g and low-g impacts. The validation data are from

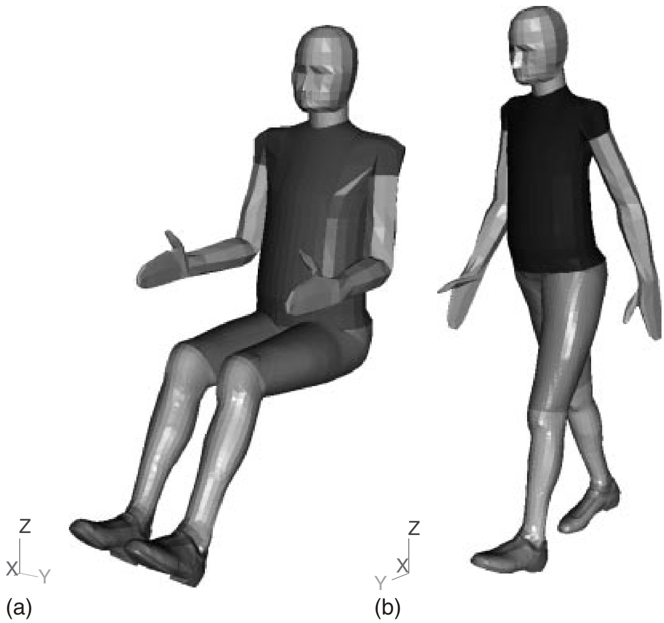


Figure 17.15 Multi-body human models in a sitting position (a) and a standing position (b). (Reproduced with permission of TNO.)

published cadaver (high-g) and volunteer (mid- and low-g) tests. This active behavior was switched off in the validation with the cadaver tests.

17.9 Finite Element Models of ATDs

The designs of current dummies are created in a CAD software environment and all their segments and components are presented in 2D drawings or 3D models (Haffner *et al.*, 2001). Thus full re-creation of dummies as a *finite element model* is possible. Manufacturers offer highly detailed and fully validated finite element models of their dummies and support many formats of FEM programs. A variety of modeling techniques are used to represent the dummy components by finite elements. While 3D models describe ATD parts explicitly, they are represented in the FEM model in simplified form and further are modeled with finite elements available in the FEM program used. It is accomplished by two basic element types: solid and shell elements. Rigid parts are modeled by *solid elements* with assigned mass properties. Shell elements are used for modeling of vinyl material covering rigid elements. Shell elements also create the outer *surface* of dummy segments for contact purposes (Kan, Marzougui, and Bedewi, 2003; Mohan *et al.*, 2007). FEM dummy models consist of several assemblies, for example, head, neck, torso, pelvis, arm, and leg, corresponding to physical dummy segments (Figure 17.17) (*http://www.humaneticsatd.com/virtual-models/finite-element/available-models*).

The FEM dummy model can contain ∼40 000 elements whereas the model of the lower extremity consists of 3521 hexagonal elements (Varellis, Campbell, and Tannous, 2004). The geometric features of existing dummies are also acquired by reverse engineering techniques. Physical objects are measured using, for example, coordinate measuring machines or scanners and the measured data are reconstructed into a CAD model (Mohan *et al.*, 2007).

17.10 Finite Element Human Models

The FEM enables full human body models to be created. FEM models include external anthropometric features, skeletal system, soft tissues (fat, skin), muscles, and internal organs (such as the brain, heart, aorta, lungs, stomach, spleen, kidneys, and bowels). von Merten *et al.* (2008) described a procedure for acquiring the shape and external dimensions of the body and internal organs. The properties of biological materials differ significantly from the materials used in technology. These are the materials of non-homogeneous structure and of non-linear, hyperelastic, and strain rate-dependent characteristics. Owing to the complexity of whole-body finite element models, segment finite element models are recommended. Therefore, comprehensive tests of finite element segment models were

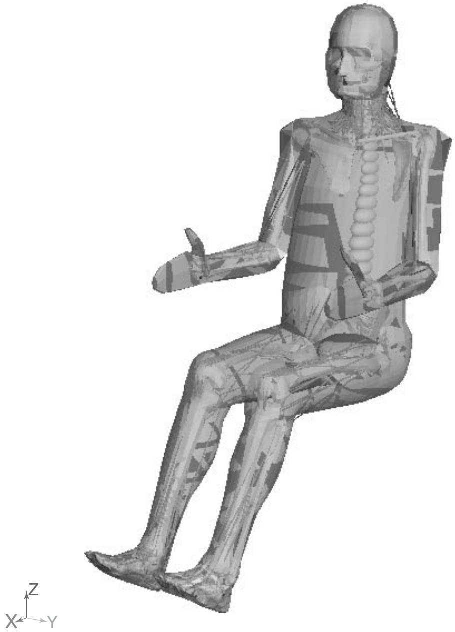


Figure 17.16 Active human model. (Reproduced with permission of TNO.)

conducted (Roberts *et al.*, 2007; Roth, Raul, and Willinger, 2010). Previously described facet human models allow accurate analysis of human kinematics, but the FEM models contribute to a better understanding of injury mechanism.

17.11 Digital Human Models

ATD material models and human body models derived from them provide accurate predictions of human kinematics and the global and local deformations in the various body parts resulting from road accidents or other emergency situations.

Digital human models are planned to be used for modeling of the human body in different working situations. They are models with a detailed body segments description. They are anthropometrically and biomechanically accurate, and also visually realistic. For creation of the models, anthropometric databases are used, that is, BODYSPACE (Pheasant and Haslegrave, 2005) and the Anthropometry Database of Japanese 1997–1998 (Digital Human Research Center, 2002). Thanks to smooth skin human modeling and deformable mesh technology, visually and anthropometrically accurate body shapes are achieved. According to the published data, the surface of the skin is mapped within human body modeling programs to internal skin points. They are also used for recognition of collisions, and can be displayed in various graphic forms from wireframe models to models

Figure 17.17 Hybrid III 50th percentile FE model. (Reproduced with permission of Humanetics Innovative Solutions, Inc.)

using advanced non-uniform rational B-spline (NURBS) technology (Piegl, 1991; Piegl and Tiller, 1987, 1995). Contemporary programs offer models from different nations and regions of the world, including those with gender, age, and body height defined. Mutual proportions of the lengths of the upper and lower extremities, and also their relations to the body height can be modeled. Moreover, disparities in body construction; so-called sitting giants and sitting dwarfs, can be displayed. These models allow a wide variety of analyses to be performed of workplace designs and better design of interior spaces for cars, trucks, airplanes, and other equipment. For this purpose, the models are animated in a variety of body postures. Body postures such as bending, kneeling, crouching, sitting, and climbing can be generated with complex animation. Also models with hand gripping postures, with the hand straightened and slack, with straight and bent single fingers, are available (ErgoMAX, 1999).

Digital human models placed in the work environment support the assessment of the design properties of operating machines. In the mining industry, people working underground in a confined space are exposed to collisions with stationary and moving elements of the surroundings. The dimensions of minimal passages in longwall systems are defined by standards, for example, PN EN 1804-1 (PKN, 2011) (Figure 17.18a). Current passage measurements are reduced by control and supply elements of roof support sections. Anthropometric features of the miner and his wearable protective equipment additionally contribute to limitations of freedom of movement (Figure 17.18b). Hence criteria of assessment given by standards

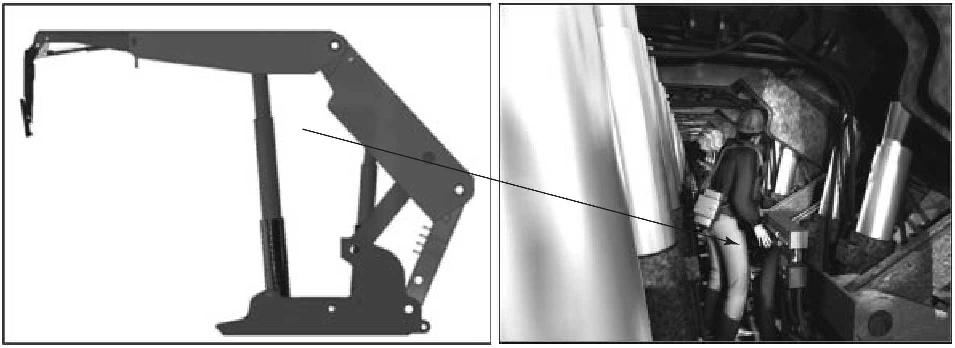


Figure 17.18 Design dimensions of minimal passages resulting from geometric dimensions (a) and actual passages measurements (b).

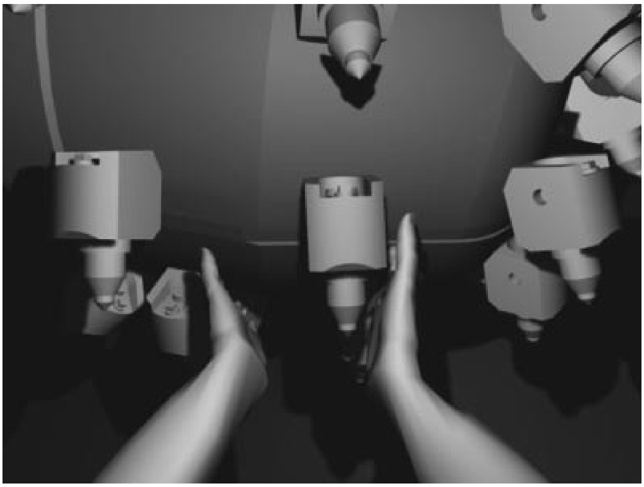


Figure 17.19 Spatial limitations in manual operations.

could be a prerequisite but are not always sufficient. Also with manual operations, the problem of minimal space enabling access to the operated elements occurs. The feasibility of manual operations is often limited by anthropometric features of the hands (Figure 17.19).

Manual operations can also be disturbed in a confined space by collision with the surrounding environment. Analyses of machine assembly, repairs, and servicing operations with the use of digital human models indicate the operating conditions that can lead to awkward body postures (IAMTECH, 2004) (Figure 17.20). Early detection of awkward body postures and overload of the musculoskeletal system allows the prediction of injuries (Ambrose *et al.*, 2005; Gallagher, 2006).

Digital human models support comprehensive task analysis, for example, the Jack program implemented the OWAS (Finnish Institute of Occupational Health,

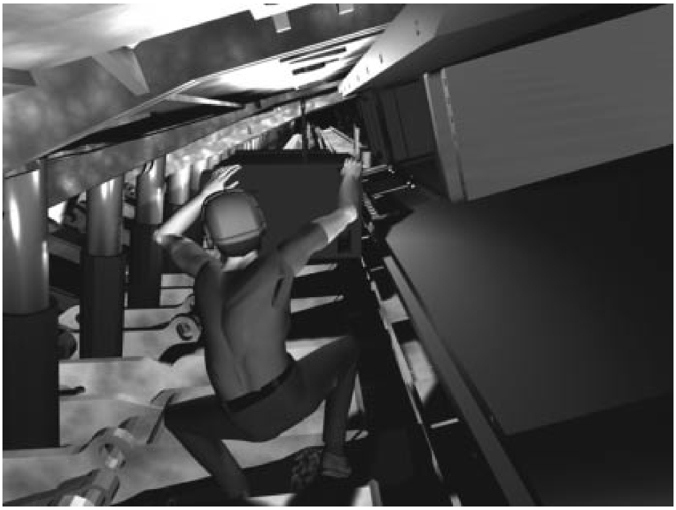


Figure 17.20 Awkward body postures evoked by the environmental conditions.

1999) and RULA (Osmond Ergonomics, 2004) methods. These evaluate the relative discomfort of a work posture, exposure to the risk of upper limb disorders, and the percentage of a worker population that has sufficient strength to perform a task based on posture. The NIOSH lifting analysis assesses symmetrical and asymmetric lifting tasks.

The complexity of the human body cannot be expressed by a single model or program. In addition to models describing the external structure of the human body, biomechanical models have also been developed. The AnyBody Modeling System (AMS) is a general-purpose software for musculoskeletal multi-body modeling and simulation (AnyBody Technology, 2011). The system has an open architecture and models are defined using a script language that gives full control of the mechanical system and allows for easy exchange of the models. The more complex parts of the human body model are available for import from an open-source library, the so-called model repository. The system provides muscular force analysis, estimates human musculoskeletal loads, and also assesses human comfort (Rasmussen, 2005). The structure of the AnyBody Modeling System is given in Figure 17.21. Digital human models show differentiated degrees of integration with CAD systems, in which models of elements from a virtual work environment are created. Integration of musculoskeletal simulations with posture modeling is indispensable for carrying out advanced biomechanical analyses, for example, by using a script file describing an anthropometric model for biomechanical procedures (Paul and Lee, 2011).

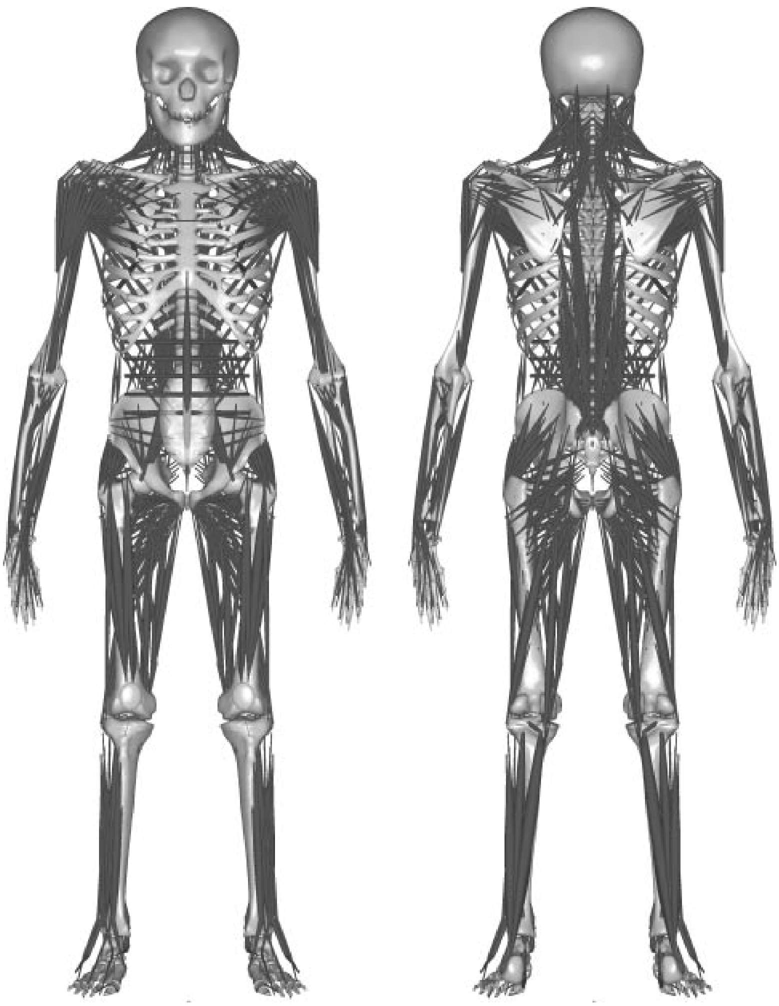


Figure 17.21 Model supporting biomechanical analysis developed in the AnyBody Modeling System.

17.12
Modeling of Phenomena

Specialized engineering methods are used to predict, analyze, and assess natural phenomena within very complex virtual working environments, and the contributions of some of them to loss prevention are further described below. FEMs are currently widely used to solve structural, fluid, and multi-physics problems. The methods are used to describe, among others, phenomena which take place in engineering materials and structures subjected to external loads.

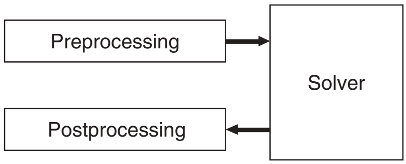


Figure 17.22 Main software modules for modeling of phenomena.

CFD as a field of fluid mechanics gives the basis for detailed numerical methods for solving the problem of fluids flow. *Multi-body system* (MBS) formalism provides an algorithmic, computer-aided approach to model, analyze, simulate, and optimize the motion of interconnected bodies. The phenomenon of motion of constrained bodies is described by means of equations that result basically from Newton's second law with the addition of constraint conditions.

In all of these methods, the same basic approach is followed. Three main modules are present in many computer programs (Figure 17.22):

- **Preprocessor** – responsible for the preparation of computational tasks
- **Solver** – responsible for calculations
- **Postprocessor** – responsible for processing and visualization of the results.

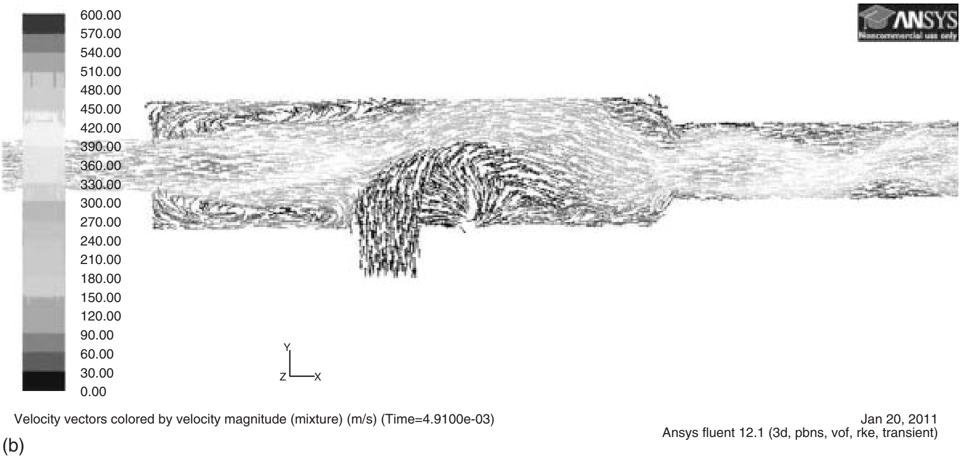
Preprocessing comprises the definition of the physical model of the problem (physical bounds), which is mostly described by means of geometric features. In FEM and CFD, the volume of the model is divided into elements. The boundary conditions are determined. Depending on the phenomenon, the conditions can be as follows: a method of model fixing and forces acting on it, material properties, conditions of contact, initial speed, fluid behavior, and properties at the boundaries. The computational model is established.

Geometric models used in modeling of phenomena are mainly prepared in CAD systems and they are transferred to preprocessors using data exchange formats (e.g., PHIGS, ACIS, Parasolid). In preprocessors they undergo changes or simplifications resulting from solver requirements. A mesh spreads over the model surface.

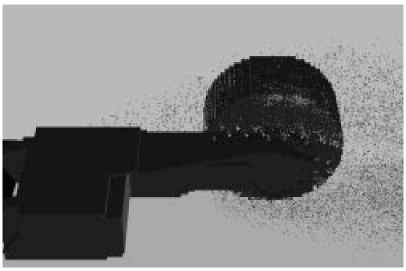
The *solver* comprises numerical methods and algorithms to solve and analyze complex equation systems describing the analyzed phenomenon. As a result of discretization and numerical solution of partial differential equations describing the flow, it is possible to determine approximately the velocity distribution, pressure, temperature, and other parameters of the flow.

Postprocessing transforms calculation results into the computer visualization and formulates textual reports. During extraction of coal, a huge amount of coal dust is generated, and is a reason for both explosion hazards and hazards to the airways of miners, causing pneumoconiosis. Spray systems are installed on cutting machines to control the concentration of airborne dust. The phenomena of coal dust generation and its propagation and also the creation and propagation of air–water suspensions are modeled by the CFD method. The models of spray nozzles created in CAD software (Figure 17.23a) are transferred to the preprocessor

(a)



(b)



(c)

Figure 17.23 Assessment of spraying efficiency: geometric model of the air–water spray nozzle (a), local CFD model (b), and global CFD model (c).

of CFD software. In Figure 17.23b, the results of simulation of the distribution and range of air–water mixtures which determine the efficiency of dust control are shown. Simulation of operation of the spray nozzles arranged on the periphery of the cutting head of the longwall shearer can be seen in Figure 17.23c, which shows an image of the combined action of the nozzles placed on the rotating cutting head. The distribution and range of air–water mixtures for different variants of nozzles and nozzle layouts are analyzed. Therefore, optimal solutions of designing the features of nozzles are achieved (Prostański *et al.*, 2009).

Dynamic phenomena that occur in MBSs can be dangerous for the physical coherence of interconnected components. A suspended monorail used for transportation of loads in underground mines is an example of MBS. Using the MBS software, a calculation model is created (Figure 17.24a) (*http://www.ansys.com/*).

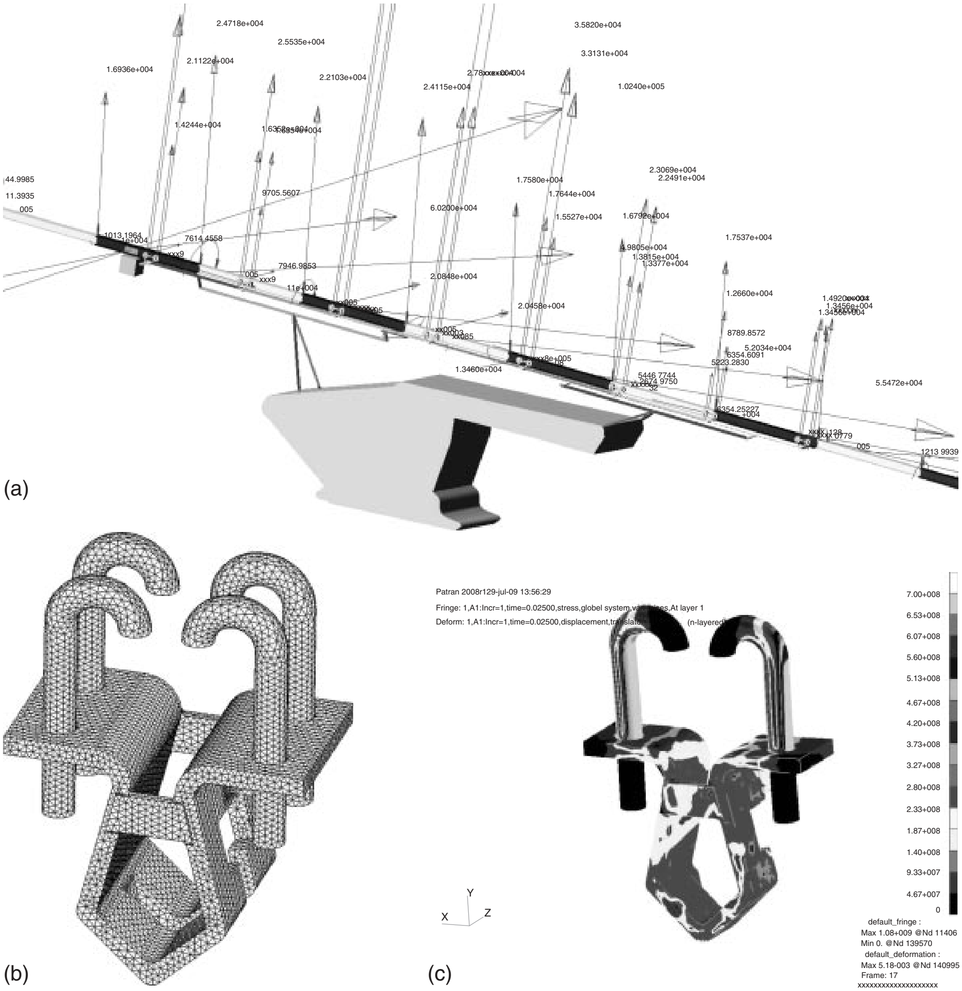


Figure 17.24 Complex multi-body system and finite element method analysis of a fastener: MBS model for dynamic braking forces calculation (a) and FEM model (b) for the creation of the map of reduced stresses (c).

For emergency braking on declined sections of a monorail route, reaction forces caused by the transported powered roof support were calculated. They were then imported to the FEM calculations model of the fastener (Figure 17.24b). A map of reduced stresses is shown in Figure 17.24c. All parts of the monorail are exposed to moisture, causing corrosion, and cross-sections of bearing elements can therefore be impaired by corrosion. Additionally dynamic forces in the suspension parts of the monorail can lead to theirs breaking. Figure 17.25 shows the effects of this kind of destruction. The fastener supported monorail carrying mining rail carriages broke, and some of them fell.

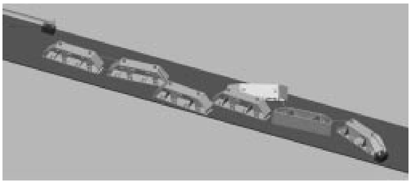


Figure 17.25 Destroyed passenger-carriages of an suspended monorail after breaking of fastener weakened by corrosion. (Reproduced with permission from TNO.)

17.13 Conclusion

From the content of this chapter we can draw the conclusion that the virtual working environment is a reflection of the existing real work environment as well as their projection. The existing real work environment brings the scenarios of processes, which can lead to *losses*, considered as

- damage to health or loss of life of the worker and
- destruction material structures.

Computer models of designed material objects (structures) and computer simulations of planned processes need these scenarios to identify the hazards that endanger the health of workers represented by human body models.

The ''scenery'' of the virtual working environment consists of computer models. The computer models in a simplified form present the technical means as geometric objects, as MBSs, or as a set of finite elements. Human body models consist of multi-body segments, of 2D or 3D finite elements, and also appear in a digital form. The behavior of human models results from the tests carried out on material dummies.

Potential hazards ''embedded'' in the scenarios of real situations are modeled in the form of phenomena, which can have a negative impact on human safety or health. The range of phenomena modeled is fairly large, with an upward trend. Phenomena of physical, chemical, and biomechanical natures occur during the static or dynamic processes. Special methods for validation of the model were developed, which can increase the ability of modeling procedures.

The virtual working environment originally was situated in the early stages of the product life-cycle. Current applications prevent losses also at the operational stages through more efficient training methods.

References

Ambrose, D.H., Bartels, J., Kwitowski, A., Gallagher, S., and Battenhouse, T.R. (2005) *J. Saf. Res.*, **36**, 387–397.

AnyBody Technology (2011) AnyBodyTutorials. The AnyBody Modeling System, Version 5.1.0, AnyBody Technology, Aalborg, *http://www.anybodytech.com/652.0.html* (last accessed 5 July 2012).

Cheng, H., Obergefell, L.A., and Rizer, A.L. (1994) Generator of Body (GEBOD) Manual. Report No. AL/CF-TR-1994-0051, NTIS, Springfield, VA, *http://www.dtic.mil/*

cgi-bin/GetTRDoc?AD=ADA289721 (last accessed 5 July 2012).

Cornelius, K.M. and Turin, F.C. (1997) A case study examining cumulative trauma exposure of coal mine workers, in *Advances in Occupational Ergonomics and Safety* (eds B. Das and W. Karwowski), IOS Press, Amsterdam.

CoVan, J. (1995) *Safety Engineering*, John Wiley & Sons, Inc., New York.

Digital Human Research Center (2002) Anthropometry Database of Japanese 1997–1998, Digital Human Research Center, National Institute of Advanced Industrial Science and Technology, Tokyo.

Ding, X., Cheng, Y., Lian, W., Zhu, F., and Zhou, Z. (2011) Improving the Accuracy of Hybrid III-50th Percentile Male FE Model, SAE Technical Paper 2011-01-0018, SAE International, Warrendale, PA.

Dudek, M., Świtoñski, E., Winkler, T., Prostański, D., Wyrobek, E., Tokarczyk, J., and Bojara, S. (2003) Computer Aided Methods for Designing Self-Propelled Roadheading Machines. Monograph No 2, CMG KOMAG, Mining Mechanization Centre KOMAG, Gliwice (in Polish).

Enderle, G., Kansy, K., and Pfaff, G. (1984) *Computer Graphics Programming. GKS – The Graphics Standard*, Springer, Berlin.

ErgoMax (1999) ANTHROPOS-ErgoMAX. User Guide Version 3.0, IST GmbH, Kaiserslautern.

Finnish Institute of Occupational Health (1999) OWAS (Ovako Working Posture Assessment System) ,*http://www.ttl.fi/en/ergonomics/methods/workload_exposure_methods/table_and_methods/Documents/OWAS.pdf* (last accessed 5 July 2012).

Gallagher, S. (1997) *Spine*, **22** (16), 1864–1872.

Gallagher, S. (2006) Working in unusual or restricted postures, in *Interventions, Controls, and Applications in Occupational Ergonomics (The Occupational Ergonomics Handbook)*, 2nd edn (eds W.S. Marras and W. Karwowski), CRC Press, Boca Raton, FL, pp. 43.1–43.16.

Gallagher, S., Landen, D.B., and Fotta, B. (1997) An analysis of sprain/strain and repetitive trauma injuries in the coal mining industry from 1986–1995. In Proceedings of the Human Factor and Ergonomics Society 41st Annual Meeting, Albuquerque, vol. 2.

Gedliczka, A. (2001) Atlas of Human Body Measures, Central Institute of Labour Protection, Warsaw (in Polish).

Gregor, M., Budzel, F., Stefanik, A., and Plinta, D. (2008) 3D laser scanning in digitization of current production systems. In Preprints of 9th IFAC Workshop on Intelligent Manufacturing Systems (IMS '08), Poland, October 9–10 (eds C.E. Pereira, O. Zaikin, and Z.A. Banaszak), International Federation of Automatic Controls, Szczecin, pp. 137–144.

Haffner, M., Eppinger, R., Rangarajan, N., Shams, T., Artis, M., and Beach, D. (2001) Foundations and elements of the NHTSA THOR alpha ATD design. In Proceedings of the 17th International Technical Conference on the Enhanced Safety of Vehicles, Amsterdam.

Hummel, V. and Westkämper, E. (2006) *Learning Factory for Advanced Industrial Engineering – Integrated Approach to the Digital Learning Environment and the Physical Model Factory*. in Production Engineering. Knowledge-Vision-Framework Programmes. (ed. E. Chlebus), Oficyna Wydawnicza Politechniki Wroclawskiej, Wroclaw, pp. 215–227.

IAMTECH (Increasing the Efficiency of Roadway Drivages through the application of Advanced Information, Automation and Maintenance Technologies), RFCS Coal RTD Programme, Contract No. RFC-CR-04001.

Kaleps, I., White, R.P., Beecher, R., Whilestone, J., and Obergefell, L. (1988) Measurement of Hybrid III Dummy Properties and Analytical Simulation Database Development. Summary Report. AAMRL-TR-88-005, Harry G. Armstrong Aerospace Medical Research Laboratory, Human Systems Division, Air Force Systems Command, Wright-Patterson Air Force Base, OH.

Kan, C.D., Marzougui, D., and Bedewi, N. (2003) Development of a 50th precentile hybrid dummy model. Presented at the 4th European LS-DYNA Users Conference, Ulm, May 22–23, 2003.

Määttä, T. (2003) Virtual Environments in Machinery Safety Analysis, VTT Publication 516, VTT Technical Research Centre of Finland, Espoo.

MADYMO (2011) MADYMO Human Models Manual, Release 7.4, TNO Automotive Safety Solutions, Delft.

Manning, J.E. and Happee, R. (1998) Validation of the MADYMO Hybrid II and Hybrid III 50th-percentile models in vertical impacts. Presented at the RTO HFM Specialists' Meeting on Models for Aircrew Safety Assessment: Uses, Limitations and Requirements, Wright-Patterson Air Force Base, Ohio, 26–28 October 1998, RTO MP-20.

Mayton, A.G., Jobes, C.C., Ambrose, D.H., and Kittusamy, N.K. (2010) *Trans. Soc. Min. Metal. Explor.*, **326**, 132–142.

Meijer, R., Hasselvan, E., Broos, J., Elrofai, H., Rooijvan, L., and van Hooijdonk, P. (2012) Development of an active multi-body human model that predicts active and passive human behaviour. Submitted to IRCOBI Conference 2012.

MINTOS (2007) Improving Mining Transport Reliability. Contract No. RFCR-CT-2007-00003, Research Program of the Research Fund for Coal and Steel, European Commission.

Mohan, P., Marzougui, D., de Velde, R., and Kann, C.D. (2007) Development of detailed finite element dummy models. Presented at the 6th LS-DYNA Anwenderforum, Frankenthal.

MSC Software (2010) *Dytran 2010 Example Problem Manual*, MSC Software, Santa Ana, CA.

NIST/SEMATECH (2012) Percentiles. In e-Handbook of Statistical Methods, *http://www.itl.nist.gov/div898/handbook/prc/section2/prc252.htm* (last accessed 26 March 2012).

Osmond Ergonomics (2004) RULA – Rapid Upper Limb Assessment, *http://www.rula.co.uk/* (last accessed 5 July 2010)

Patran (2010) Reference Manual Part 6: Results Postprocessing, *http://simcompanion.mscsoftware.com/infocenter/index?page=content&channel=DOCUMENTATION&cat=PATRAN_DOCUMENTATION* (last accessed 11 September 2012).

Paul, G. and Lee, W.C. (2011) Interfacing Jack and AnyBody: towards anthropometric musculoskeletal digital human modeling. In Proceedings of the 1st International Symposium on Digital Human Modeling, Lyon, June 14–16, 2011.

Pheasant, S. and Haslegrave, C.M. (2005) *Bodyspace: Anthropometry, Ergonomics and the Design of Work*, 3rd edn, Taylor & Francis, London.

Prostański, D., Pieczora, E., Bałaga, D., and Rojek, P. (2009) Air–water sprinkling – cheaper, comfortably and safely. In 33rd Conference on Safety in Mines Research Institutes, Wisła, September 15–18, 2009. Górnictwo i Środowisko, Prace Naukowe GIG 2009 No. 3/1, pp. 179–190 (in Polish).

Piegl, L. and Tiller, W. (1987) *Comput.-Aided Des.*, **19** (9), pp. 485–498.

Piegl, L. (1991) *IEEE Comput. Graph. Appl.*, pp. 55–71.

Piegl, L.and Tiller, W. (1995) *Comput.-Aided Des.*, **28** (9), pp. 699–706

PKN (Polish Committee for Standardization) (2011) PN EN 1804-1 + A1:2011. *Machines for Underground Mines. Safety Requirements for Hydraulic Powered Roof Supports. Support Units and General Requirements.* Polish Standard (in Polish).

Rasmussen, J. (2005) Musculoskeletal simulation – (dis)comfort evaluation. *Sound Vibr.*, **39** (5), 8–9.

Roberts, J.C., Merkle, A.C., Biermann, P.J., Ward, E.E., Carkhuff, B.G., Cain, R.P., and O'Connor, J.V. (2007) *J. Biomech.*, **40**, 125–136.

Roth, S., Raul, J.-S., and Willinger, R. (2010) *Comput. Meth. Programs Biomed.*, **99**, 25–33.

Varellis, J., Campbell, J.Q., and Tannous, R.E. (2004) Development and Validation of a Finite Element Model of the THOR Lower Extremity. Final Report, Applied Advance Scientific Analysis, Reston, VA.

von Merten, K., Peldschus, S., Muggenthaler, H., and Graw, M. (2008) *Rechtsmedizin*, **18**, 431–436.

Winkler, T., Dudek, M., Chuchnowski, W., Jaszczyk, Ł., Michalak, D., and Świeca, W. (2007) Concept of interactive electronic technical manual (IETM) on the example of mining machines, in *Hochleistungsabbaubetriebe: Viertes Internationales Kolloquium, Institute of Mining Engineering I, RWTH Aachen University, 30–31 Mai 2007* (ed. P.N. Martens), VGE Verlag, Essen, pp. 223–234.

Winkler, T., Dudek, M., Michalak, D., Tokarczyk, J., and Jaszczyk, Ł. (2008a) Knowledge based creation of safe work environment in the mining industry, in *Challenges and Visions for Mining* (eds E.J. Sobczyk, J. Sobczyk and J. Kicki), CRC Press, Boca Raton, FL, pp. 229–237.

Winkler, T., Tokarczyk, J., and Bojara, S. (2008b) *Comput. Assist. Mech. Eng. Sci.*, **15** (1), 53–66.

Winkler, T., Dzieniakowski, T., and Jaworski, M. (2003) Problems of the comfort and discomfort in technology and medicine, in *Quality of Work and Products in Enterprises of the Future* (eds H. Strasser, K. Kluth, H. Rausch, and H. Bubb), Ergonomia Verlag, Stuttgart, pp. 171–174.

Winkler, T., Michalak, D., and Bojara, S. (2004) Computer visualization of risk factors which occur during mining machines assembling in the underground workings, in *Mine Planning and Equipment Selection 2004* (eds M. Hardygóra, G. Paszkowska, and M. Sikora), Balkema, Leiden, pp. 883–886.

Winkler, T. and Schmid, M. (2008) Interactive 3D supports underground repair and maintenance of road heading machines and shearer loaders. In Proceedings of the 21st World Mining Congress, Cracow, Poland, 7–11 September 2008. Session: Information Technology in Mining.

Winkler, T. and Tokarczyk, J. (2011) Assessment scenarios of virtual prototypes of mining machines, in *Intelligent Automation and Systems Engineering*, Lecture Notes in Electrical Engineering, vol. **103** (eds S.I. Ao, M. Amouzegar, and B.B. Rieger), Springer, New York, pp. 175–187.