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# Development of Critical Infrastructure Resilience by Using Virtual Failure Simulations on the Example of a Power Plant

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**Abstract.** Resilience of Critical Infrastructure (CI) facilities defined as a capacity for further operation even upon changes that may result from natural or human-made disasters is extremely important from the perspective of functioning of society. Resilience of critical infrastructure facilities may be developed by taking such activities as introducing changes to their structure based on results of simulations of functioning of CI facilities. Another solution is to make use of computer simulations for better preparation of persons responsible for the functioning of CI facilities. This article describes a reference CI facility with potential scenarios of development of emergency situations and with a set of optional courses of an emergency situation. The scenarios were used to prepare a training application based on virtual reality techniques with an interface allowing a wide spectrum of interactions with a virtual environment, including commands issued to other employees, to be executed.
**Keywords:** critical infrastructure, reliability, virtual reality, training application design

## 1. INTRODUCTION

Human-made and natural disasters, such as the terrorist attacks in 2001 and hurricane Katrina in 2005, highlighted the sensitivity of Critical Infrastructure (CI) systems and raised awareness of the need to protect them. To improve the protection of CI in the USA, the National Infrastructure Simulation and Analysis Centre (NISAC) and the Department of Homeland Security were established in 2001 and 2002. Similar organisations and programmes were also developed in other regions and countries. They included the European program of critical infrastructure protection, the plan of implementation of critical infrastructure protection in Germany, and the programme of critical infrastructure resilience in Great Britain [1]. In Asia, as a result of the earthquake and tsunami in Fukushima [direct cause of failure in the Japanese nuclear power plant was an extremely (14 m) high tsunami wave that broke the retaining wall and flooded the diesel generators which were installed too low; water also damaged fuel tanks for the generator sets, and one of these tanks was moved by the wave by 150 m; reactor cooling issues were noted], the Japanese national resilience programme in 2013 assigned USD 210 billion for projects to enhance overall security of energy, water, transport and other CI facilities [2]. Knowing that the majority of failures originate from the distribution system, the Chinese energy administration provided CNY 20 billion for a major repair of the grid in the period 2015–2020 to increase its reliability, quality of energy, and resilience to disturbances. Methods of modelling and simulation of functioning of CI aimed at increasing the latter's resilience drew a lot of attention in the scientific environment, among private companies, and among governmental bodies. In Poland, the National Critical Infrastructure Protection Programme was developed [3].

The term "resilience" was introduced for the first time in 1973 by Holling in the field of ecology and evolution [4]. This concept was first used to describe the capacity of an ecosystem for further functioning after changes. Nowadays resilience is widely used in numerous fields, including in relation to national disasters and risk management [5], civil infrastructure testing [6–8], systems engineering [9], power systems [10–11], etc.

Although there is no consensus as to the definition of resilience [12], its core is generally the same, i.e. it is a master concept covering a system's performance before and after catastrophic events. The study [13] presents an overview of different approaches to defining and assessing resilience, and provides three features of resilience: adaptation capacity, absorption capacity, and recovery capacity. Thus resilience can be defined as "a unit's capacity to foresee, counteract, absorb, react to, adapt to, and overcome disturbances" [14].

The study [15] presents an overview of eight modelling and simulation techniques for interdependent CI, namely: agent modelling, system dynamics, hybrid system modelling, input-output mode, holographic hierarchical modelling, critical path method, high level architecture, and Petri nets.

Additionally, seven criteria for model assessment were proposed. They include: modelling orientation, methodical design strategies, types of interdependencies, types of events for simulation, consequences of events, and data and monitoring needs. Ouyang [16] has recently made an overview of the existing approaches to modelling and simulation of CIs and has divided them into six types: empirical approaches, agent approaches, dynamic approaches, economic approaches, network approaches, and other. The existing research has been classified and reviewed in terms of basic principles.

Energy infrastructures include electricity grids, gas networks and fuel networks. Among all critical infrastructure sectors, energy infrastructure can be considered the essential as it secures the functioning of facilities in all of the remaining critical infrastructure sectors. For instance, water supply and sewer networks are based on power systems which ensure operation of the networks' pumps. IT and communication systems are based on power systems in terms of execution of data transmission tasks. Transport systems are based on fuel networks to obtain power for all types of vehicles. The dependence of other critical infrastructures on the power grid may cause the latter to be susceptible to disturbances. Disturbances in a power system may be transferred to other dependent infrastructure systems, and even back to the sources of failure [17–18]. This sequential and accumulating feature of failure increases the susceptibility of a power grid. Energy infrastructure is also sensitive to climate change. Rising sea level and an increasing frequency of big storms lead to serious floods in coastal areas where numerous pieces of energy infrastructure [19], such as power plants, natural gas plants, and petroleum and gas refineries are located. Moreover, low probability events, such as hurricanes and terrorist attacks, exert great influence on the further functioning of energy infrastructure.

On the basis of the aforementioned significance and susceptibility to hazards, resilience of energy infrastructure has become an urgent and important subject of research. This issue is dealt with using various methods. In many publications, resilience of energy infrastructure is simulated as an optimum operating issue [20–25]. Some researchers use the agent based modelling method to reveal complicated interactions between power system components [26–29]. Others improve traditional topological indicators of power grids by embodying their physical behaviour [30]. Furthermore, in response to the appearance of "big data" resources, in some research large-scale data analysis in energy resilience is used, in particular with regard to power grid testing [31–32].

## 2. CRITICAL INFRASTRUCTURE REFERENCE FACILITY

For the purposes of development of the subject-matter study, including a scenario of development of critical infrastructure facility emergency situations, Dolna Odra Power Plant (DOPP, Poland) was selected as the reference facility.

It belongs to Dolna Odra Power Plants Complex (together with Pomorzany Power Plant and Szczecin Power Plant, Poland), is owned by PGE Mining and Conventional Power Generation - Polish Joint Stock Company, and is located in Nowe Czarnowo near Gryfino, Poland (Western Pomerania province). Virtual environment of DOPP is illustrated in Fig. 1.

DOPP was erected in 1974–1977 and upgraded in the 90s. This system- and unit-based, conventional power plant with an open cooling system is currently provided with 8 units. Units 1–2 and units 5–8 ensure installed power at a level of 1,362.00 MWe and thermal power at a level of 100.81 MWt, whereas units 3–4 are taken out of operation. Hard coal is used as the fuel in the process of electricity generation. Biomass is also co-fired at the plant on an industrial scale.

## 3. SCENARIO OF DEVELOPMENT OF EMERGENCY SITUATION OF CRITICAL INFRASTRUCTURE FACILITY

The scenario of development of an emergency situation of a critical infrastructure facility based on the example of DOPP covers the following sequence of events initiating conditions that may affect occupational health and safety, as well as continuity of operation of the reference facility being analysed:

1) Representatives of an unidentified group of hackers enter the DOPP premises and provide themselves with physical access to an internal, isolated data communication system of the power plant. This physical access is a point-type (intermediate) connection to the above system with remote access function.
2) Representatives of an unidentified group of hackers carry out remote hacking into the internal isolated data communication system of the power plant via the intermediate connection (physically located outside of the DOPP premises). By interacting with functional modules of the distribution centre, they falsify the results of measurements of the boiler tank filling level displayed at the distribution centre. They also provide images from cameras set on unit 7 and its immediate vicinity.
3) Personnel of the distribution centre is convinced that the amount of coal in the boiler tank is lower than in reality. As a consequence, the personnel activates the boiler filling function and keeps it active even when the tank has in reality been filled.
4) Coal overflows the boiler tank, and coal lumps fall into the surrounding elements of infrastructure and systems, machinery, and equipment. The lumps damage, for instance, the coal conveyor and mill control system supply cables. As a result of the supply cable damage, sparking occurs and smouldering of the lumps that came out of the overfilled tank is initiated. Coal lumps coming out of the tank trigger the release of a dust and air mixture into spaces located at the overfilled boiler tank and at the boiler.

5) The emergency situation is not identified by DOPP personnel as all cameras oriented towards the relevant locations show the images replaced by the representatives of the unidentified group of hackers. The field engineer is involved in monitoring of the adjacent units and does not walk through the zone under analysis.

Despite the fact that the list of critical infrastructure components is confidential, it was assumed that DOPP may be a component of the system supplying energy, raw materials for power industry and fuels, thus requiring special protection against any factors that may affect the continuity of its operation. Drawing upon good industry practices, particular attention should be paid to physical protection, technical protection, personal protection, data transmission protection, legal protection and recovery plans.

## 4. LIST OF SCENARIO OPTIONS

On the basis of an analysis of the network of safety factors, and in connection with the training-related intended purpose of the scenario, the following options for its development have been formed:

Option 1). Sparking from the belt conveyor and mill control system supply cables causes ignition of the dust and air mixture, explosion (deflagration), mill damage, immediate secondary explosion (deflagration) of the mixture inside the mill, and fire caused by the distribution of the flammable material around the explosion zone. Two adjacent units (6 and 8) are damaged and trip. 3 field engineers are injured. They are unable to leave the hazard zone on their own. 2 employees working in the remaining units go to rescue them.

Option 2). Sparking from the belt conveyor and mill control system supply cables causes ignition of a layer of coal dust that was accumulated on adjacent components and fire of this layer. The smoke being released hinders identification of the location of the fire. The fire alarm system installed in common circulation routes detected the fire hazard and caused unit 7 to trip. 3 employees run from the adjacent units and carry out initial identification of the hazard.

Option 3). Fire hazard is identified by a relevant field engineer. Sparking from the belt conveyor and mill control system supply cables causes electric shock to the engineer, who loses consciousness. Loss of wireless communication with this employee is regarded by the distribution centre employee as an emergency medical condition. He/she selects another field engineer to verify the condition of the first employee.

Option 4). Fire hazard is identified by a relevant field engineer. Coal lumps coming out of the boiler tank hit his/her head, causing loss of consciousness. Loss of wireless communication with this employee is regarded by the distribution centre employee as an emergency medical condition. He/she selects another field engineer to verify the condition of the first employee.

Option 5). Coal lump layer fire initiates ignition of a layer of coal dust that has accumulated on adjacent components. The smoke being released hinders identification of the location of the fire. The field engineer who notices the accumulation of smoke loses orientation and consciousness. The smell of smoke is perceived by 1 employee servicing cleaning equipment. He/she notices the injured person and goes to help him/her.

Fig. 1. Virtual environment presenting an emergency situation (explosion and fire) in a critical infrastructure facility such as a power plant.

Fig. 2. Illustration of interface to issue commands to the second employee and to inform about events (left) and send a message to a corresponding recipient – select the recipient from the list (right).

## 4. CONCLUSIONS

It is assumed that the utilisation of realistic simulations based on virtual reality techniques will increase the effectiveness and efficiency of this type of training, which is currently conducted using traditional forms of training and simple, schematic computer games or RPGs (*Role Playing Games*) without computers.

Virtual reality can be used to illustrate complex, multi-optional training scenarios that show the development of emergency situations even in such complicated and complex critical infrastructure components, such as power plants and combined heat and power plants.

HMD (*Head Mounted Display*) goggles used on the head and controllers held in the hands allow for free observation of the virtual environment on the basis of a stereoscopic image, and for a wide spectrum of interactions with the virtual environment. The user, seeing avatars of his/her hands, can lift and handle various items, activate machines and perform repairs. An almost complete set of manual actions is available. Utilisation of an additional interface extends the scope of available actions by such activities as direct communication with personal avatars (including e.g. issuing commands to the combined heat and power plant employees – see Fig. 2) or sending messages using selected means of communication (computer, telephone, radio-telephone, etc.).

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## REFERENCES

[1] Ouyang, Min. 2014. "Review on modeling and simulation of interdependent critical infrastructure systems". *Reliability Engineering and System Safety* 121 : 43-60.

[2] DeWit, Andrew. 2016. "Japan's `National Resilience' and the legacy of 3–11". *The Asia-Pacific Journal* 14 (6) : 1-7.

[3] https://rcb.gov.pl/wp-content/uploads/Standardy-s%C5%82u%C5%BC%C4%85ce-zapewnieniu-sprawnego-funkcjonowania-IK-%E2%80%93-dobre-praktyki-i-rekomendacje.pdf. (2022).

[4] Holling, C.S. 1973. "Resilience and stability of ecological systems". *Annual Review of Ecology and Systematics* 4 (1) : 1-23.

[5] Cutter, L. Susan, Kevin D. Ash, Christopher T. Emrich. 2014. "The geographies of community disaster resilience". *Global Environmental Change* 29 : 65-77.

[6] Bocchini, Paolo, Dan M. Frangopol. 2012. "Optimal resilience- and cost-based postdisaster intervention prioritization for bridges along a highway segment". *Journal of Bridge Engineering* 17 (1) : 117-129.

[7] Bocchini, Paolo, Dan M. Frangopol, Thomas Ummenhofer, Tim Zinke. 2013. "Resilience and sustainability of civil infrastructure: toward a unified approach". *Journal of Infrastructure Systems* 20 (2) : 04014004.

[8] Frangopol, M. Dan, Paolo Bocchini. 2011. Resilience as optimization criterion for the rehabilitation of bridges belonging to a transportation network subject to earthquake. In *Proceedings of the Structures Congress*, Las Vegas NV, USA, 14-16.04.2011.

[9] Dessavre, Dante Gama, Jose E. Ramirez-Marquez, Kash Barker. 2016. "Multidimensional approach to complex system resilience analysis". *Reliability Engineering & System Safety* 149 : 34-43.

[10] Bie, Zhaohong, Yanling Lin, Gengfeng Li, Furong Li. 2017. "Battling the extreme: a study on the power system resilience". *Proceedings of the IEEE* 105 (7) : 1253-1266.

[11] Watson, Jean-Paul, Ross Guttromson, Cesar Silva-Monroy, Robert Jeffers, Katherine Jones, James Ellison, Charles Rath, Jared Gearhart, Dean Jones, Tom Corbet, Charles Hanley, La Tonya Walker. 2014. *Conceptual framework for developing resilience metrics for the electricity, oil, and gas sectors in the United States.* Sandia Report SAND2014-18019. Sandia National Lab, Albuquerque, USA.

[12] Hosseini, Seyedmohsen, Kash Barker, Jose E. Ramirez-Marquez. 2016. "A review of definitions and measures of system resilience". *Reliability Engineering & System Safety* 145 : 47-61.

[13] Francis, Royce, Behailu Bekera. 2014. "A metric and frameworks for resilience analysis of engineered and infrastructure systems". *Reliability Engineering & System Safety* 121 : 90-103.

[14] Carlson, J., R. Haffenden, G. Bassett, W. Buehring, M. Collins III, S. Folga, F. Petit, J. Phillips, D. Verner, R. Whitfield. 2012. *Resilience: theory and application*. Argonne National Lab, Argonne, USA.

[15] Eusgeld, Irene, David Henzi, Wolfgang Kröger. 2008. *Comparative evaluation of modeling and simulation techniques for interdependent critical infrastructures*. Scientific Report. Laboratory for Safety Analysis, ETH Zurich.

[16] Ouyang, Min. 2014. "Review on modeling and simulation of interdependent critical infrastructure systems". *Reliability Engineering & System Safety* 121 : 43-60.

[17] Havlin, Shlomo, Nuno A.M. Araujo, Sergey V. Buldyrev, Cristovao S. Dias, Roni Parshani, G. Paul, H. Eugene Stanley. 2010. "Catastrophic cascade of failures in interdependent networks". *Nature* 464 (7291) : 1025-1028.

[18] Huang, Chun-Nen, James J.H. Liou, Yen-Ching Chuang. 2014. "A method for exploring the interdependencies and importance of critical infrastructures". *Knowledge- Based Systems* 55 : 66-74.

[19] Bollinger, L. Andrew. 2011. *Evolving climate-resilient energy infrastructures*. TU Delft, Delft, Netherlands.

[20] Arif, Anmar, Zhaoyu Wang, Jianhui Wang, Chen Chen. 2018. "Power distribution system outage management with co-optimization of repairs, reconfiguration, and DG dispatch". *IEEE Transactions on Smart Grid* 9 (5) : 4109-4118.

[21] Chen, Bo, Chen Chen, Jianhui Wang, Karen L. Butler-Purry. 2018. "Sequential service restoration for unbalanced distribution systems and microgrids". *IEEE Transactions on Power Systems*, 33 (2) : 1507-1520.

[22] Chen, Chen, Jianhui Wang, Feng Qiu, Dongbo Zhao. 2016. "Resilient distribution system by microgrids formation after natural disasters". *IEEE Transactions on Smart Grid* 7 (2) : 958-966.

[23] Ding, Tao, Yanling Lin, Gengfeng Li, Zhaohong Bie. 2017. "A new model for resilient distribution systems by microgrids formation". *IEEE Transactions on Power Systems*, 32 (5) : 4145-4147.

[24] Manshadi, D. Saeed, Mohammad E. Khodayar. 2015. "Resilient operation of multiple energy carrier microgrids". *IEEE Transactions on Smart Grid* 6 (5) : 2283-2292.

[25] Yuan, Wei, Jianhui Wang, Feng Qiu, Chen Chen, Chongqing Kang, Bo Zeng. 2016. "Robust optimization-based resilient distribution network planning against natural disasters". *IEEE Transactions on Smart Grid* 7 (6) : 2817-2826.

[26] Dudenhoeffer, D. Donald, May R. Permann, Milos Manic. 2006. CIMS: a framework for infrastructure interdependency modeling and analysis, Proceedings of the thirty eighth conference on winter simulation. In *Proceedings of the Winter Simulation Conference WSC 2006,* Monterey, California, USA, December 3-6, 2006.

[27] Keirstead, James, Nouri J. Samsatli, Nilay Shah. 2010. SynCity: an integrated tool kit for urban energy systems modeling. In *Energy efficient cities: assessment tools and benchmarking practices*, The World Bank, Washington, DC, USA, pp. 21-42.

[28] Li, Gengfeng, Zhaohong Bie, Yu Kou, Jiangfeng Jiang, Mattia Bettinelli. 2016. "Reliability evaluation of integrated energy systems based on smart agent communication". *Applied Energy* 167 : 397-406.

[29] P. Pederson, Donald D. Dudenhoeffer, S. Hartley, May R. Permann. 2006. *Critical infrastructure interdependency modeling: a survey of US and international research.* Technical Report INL/EXT-06-11464, Idaho National Lab, Idaho Falls, USA.

[30] Bompard, Ettore, R. Napoli, Fei Xue. 2009. "Analysis of structural vulnerabilities in power transmission grids". *International Journal of Critical Infrastructure Protection* 2 (1) : 5-12.

[31] Ji, Chuanyi, Yun Wei, Henry Mei, Jorge Calzada, Robert Wilcox, Steve Church, Timothy Hayes, et al. 2016. "Large-scale data analysis of power grid resilience across multiple US service regions". *Nat Energy* 1 (5) : 16052.

[32] Peter, H. Larsen, Kristina Hamachi LaCommare Joseph H. Eto, James L. Sweeney. 2015. *Assessing changes in the reliability of the U.S. electric power system* Lawrence Berkeley National Lab, Berkeley, USA.

# Zwiększanie odporności infrastruktury krytycznej poprzez wykorzystanie wirtualnych symulacji awarii na przykładzie elektrowni

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**Streszczenie.** Odporność obiektów Infrastruktury Krytycznej (IK) definiowana jako zdolność do dalszego działania nawet po wystąpieniu zmian, których źródłem mogą być katastrofy naturalne lub te spowodowane przez człowieka, jest niezwykle istotna z punktu widzenia funkcjonowania społeczeństwa. Zwiększanie odporności obiektów infrastruktury krytycznej może być realizowane dzięki działaniom takim jak wprowadzanie zmian do ich budowy na podstawie wyników symulacji funkcjonowania obiektów IK. Innym rozwiązaniem jest wykorzystanie symulacji komputerowych do lepszego przygotowania osób odpowiedzialnych za funkcjonowanie obiektów IK. W artykule opisano referencyjny obiekt IK wraz z potencjalnymi scenariuszami rozwoju sytuacji kryzysowych wraz zestawem wariantów przebiegu sytuacji kryzysowej. Scenariusze te zostały wykorzystane do przygotowania aplikacji szkoleniowej bazującej na technikach rzeczywistości wirtualnej z interfejsem umożliwiającym realizację szerokiego spektrum typów interakcji z środowiskiem wirtualnym, w tym wydawanie poleceń innym pracownikom.

**Słowa kluczowe:** infrastruktura krytyczna, niezawodność, rzeczywistość wirtualna, projektowanie aplikacji szkoleniowych