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SIMULATION OF MINE MATERIAL HANDLING SYSTEMS USING AutoMod

SIMULACIJA TRANSPORTNIH SISTEMA U RUDARSTVU POMOĆU AutoMod-A

Božo KOLONJA[1], Ratomir STANIĆ[2], Jovan HAMOVIĆ[1]
[1]Faculti of Mining and Geology, Belgrade, Djusina 7
[2]Open Pit Mine "Pljevlja", Pljevlja, Yugoslavia

Abstract: *Simulation is an excellent method to test design assumptions, material flow, controls logic, and manning requirements. It is often recommended for complex material flows to verify bottlenecks, maximum throughput, and queuing requirements for back up conditions. With the advanced tools available today, a simulation is generally an excellent insurance policy investment that the integrated system will perform to expectations. This paper presents a simulation modeling approach by AutoMod using actual data from the mine. Model was used to analyze current operations and future needs to determine the effects of new equipment and system modifications. The 3D AutoMod animation enhances the understanding of mining operations and the acceptance of simulation as a viable mine design and management tool.*

Key words: *simulation, material flow, 3D Auto Mod*

Apstrakt: *Simulacija predstavlja pogodan alat za testiranje projektnih pretpostavki, analizu toka materijala i upravljačke logike i procenu kapaciteta opreme itd. Posebno je pogodna za analizu složenih tokova materijala radi utvrđivanja uskih grla i redova čekanja u sistemima. Jednom rečju, simulacija predstavlja savremeni pristup za sistemsku analizu. U radu je prikazan AutoMod simulacioni model za analizu transportnog sistema na površinskom kopu. Model je korišćen za analizu postojećih operacija i budućih potreba, kako bi se odredila efikasnost opreme i modifikacija sistema. Trodimenzionalna animacija koju podržava AutoMod olakšava razumevanje rudarskih operacija i prihvatljivost simulacija kao alata za projektovanje i upravljanje rudnikom.*

Ključne reči: *simulacija, tok materijala, 3D Auto Mod*

1. INTRODUCTION

One of the main purposes of computer simulation is to imitate the operations of real-life systems or processes. Computer simulation allows rapid manipulation of the major parameters or functions of a system without the problem of continuous physical replications. Simulation has been applied in the mining industry, mainly in connection with transport systems, mining operations, mine planning and production scheduling. Most of the simulators have been developed either in general-purpose languages like Fortran or C, or in simulation languages like GPSS/H and SIMAN.

1. UVOD

Jedna od najvažnijih namena kompjuterskih simulacija je oponašanje sistema i procesa iz realnog okruženja. Kompjuterska simulacija omogućava brzo manipulisanje glavnim parametrima i funkcijama sistema bez problema koje donosi kontinualna fizička replikacija. Simulacija se u rudarstvu koristi, uglavnom, u oblasti transporta, rudarskih operacija, projektovanja i planiranja proizvodnje. Većina simulatora je razvijena u jezicima opšte namene, kao što su Fortran ili C, ili u simulacionim jezicima, kao što su GPSS/H i SIMAN.

Whether designing a new system or modifying an existing one, engineers want to take the guesswork out of finding the best possible solution. While there are many analysis methods for designing mining systems, simulation remains the method that gives the highest level of confidence a system will work. A well-written simulation model can be a valuable tool in the design, analysis, and operation of mining systems. As with most technologies there are always a number of difficulties to overcome. The same applies for conducting simulation studies in the mining environment. Included is just a few of these problems:

- Mining simulation models tend to be very complex - most mining simulation models are significant more difficult than models in the traditional simulation environment. There are always very complex decision logic, resource rules, transportation rules and process dependant operations that must be modeled in great detail.
- Time consuming process - to obtain reliable results, the models must consist of all your process detaisl, which significantly increases model development time.
- Company bureaucracies - getting commitment from all relevant parties influenced by the simulation study is very difficult.

This paper details the analysis and simulation of the material handling system at the Pljevlja coal mine. During the exploitation and reconstruction phase of the project, several problems were encountered constraining the operation of the system. The overall aim of this project was to use simulation software to firstly simulate the operations of the system and then optimize the operation of the system given the operational constraints. The optimization of the system involves developing an efficient mine operating arrangement for the haulage system. Thus the first and primary objective was to develop a working simulation model of the material handling system which is an accurate reflection of the actual haulage system. Further objectives were to:

- simulate the operational constraints which occur in the material handling system and develop an efficient operating procedure to overcome them,
- verify the true system capacity and identify bottlenecks in the system,
- analyze the design of the system and determine where simulation could have been used to optimize the system before reconstruction.

Bilo da projektuju novi sistem, ili modifikuju, postojeći, inženjeri žele da eliminišu nagađanje iz procesa pronalaženja optimalnog rešenja. Iako postoje mnoge analitičke metode za projektovanje rudarskih sistema, simulacija je metod koji daje najveći stepen pouzdanosti. Dobro napisan simulacioni model predstavlja korisnu alatku za projektovanje, analizu i eksploataciju rudarskih sistema, mada je, kao i kod većine tehnologija, potrebno prevazići nekoliko problema. Navešćemo samo nekoliko slučajeva:

- Simulacije rudarskih sistema su veoma složene – većina simulacionih modela je daleko složenija od modela tradicionalnih sistema. Veoma složena logika odlučivanja, pravila za korišćenje resursa, transportnih sistema i procesa vezanih za pojedine operacije moraju biti modelirani do najsitinijih detalja.
- Dugotrajan proces – kako bi se postigla pouzdanost rezultata, modeli moraju da uključe sve detalje procesa, što značajno uvećava vreme potrebno za razvoj modela.
- Birokratija – ostvariti aktivno učešće svih uključenih strana, zainteresovanih za simulacionu studiju, je ponekad veoma teško.

Ovaj rad daje detalje analize i simulacije sistema za transport na rudniku uglja Pljevlja. Tokom eksploatacije i rekonstrukcije sistema, pojavilo se nekoliko problema koji su ugrožavali ekonomski opravdano funkcionisanje sistema. Cilj projekta je bio da se razvije funkcionalni model sistema, a, zatim, da se rad sistema optimizuje, uzimajući u obzir operativna ograničenja. Optimizacija sistema obuhvata razvoj efikasnog transportnog sistema. Primarni cilj je bio razvijanje simulacionog modela toka materijala koji bi bio veran prikaz stvarnog sistema. Dalji ciljevi su bili:

- simuliranje radnih ograničenja koja se mogu pojaviti u transportnom sistemu i razviti efikasne operativne procedure za njihovo prevazilaženje,
- određivanje realnog kapaciteta sistema i uskih grla,
- analiza sistema i određivanje primenljivosti simulacija za optimizovanje sistema pre rekonstrukcije.

The above questions are answered by analysing different cases with AutoMod simulation model. This paper is intended to demonstrate what is possible, and thus the results obtained here are particular to this model.

2. AUTOMOD SIMULATION ENVIRONMENT

Currently there are several simulation languages that can be used for the purposes of mine research (e.g. GPSS/H, SLAM, SIMAN, WITNESS, AutoMod). The choice of a simulation language is based on several criteria, more importantly the ease of use; provision of adequate debugging and error diagnostics; capability to import data from other software such as spreadsheets and CAD packages; and ability to be combined without programming with animation/graphics environments for visualization of the mining operations. Another important consideration in our case is the ability of interfacing the simulation models with orebody modeling and ground control software systems.

AutoSimulation Inc.'s AutoMod is simulation language environment that appears to satisfy the above criteria. AutoMod is a combined continuous and discrete general purpose modeling package. This software package offers rapid generation of simulation models that can be animated. They incorporate powerful mouse driven three-dimensional CAD routines, which allow the creation of a picture of the system under modeling. The software offers an integrated development environment and interactive debugging procedures for step-by-step execution of a model to assist in the verification and validation process.

The AutoMod simulation system differs significantly from other systems because of its ability to deal with the physical elements of a system in physical (graphical) terms and the logical elements of a system in logical terms. AutoMod also offers advanced features to allow users to simulate complex movement (kinematics and velocity) of equipment such as robots, machine tools, transfer lines, and special machinery. All graphics are represented in 3D space with unlimited viewing control, including translation - rotation, scale, light-sourced solids, perspective, and continuous motion viewing.

With AutoMod the following materials handling systems in a manufacturing facility can easily be simulated: transporters (such as fork trucks or Automated Guided Vehicle (AGV) systems), conveyors, automated storage and retrieval systems, robots and bridge cranes. To define

Na navedena pitanja je odgovoreno analiziranjem različitih slučajeva pomoću simulacionog modela razvijenog u AutoMod-u. Cilj ovog rada je prikazivanje mogućnosti simulacionog modela, tako da su dobijeni rezultati specifični za razvijeni model.

2. AUTOMOD OKRUŽENJE ZA RAZVOJ SIMULACIONIH MODELA

Danas postoji više simulacionih jezika koji mogu biti korišćeni za naučno-stručna istraživanja u rudarstvu (na primer, GPSS/H, SLAM, SIMAN, WITNESS, AutoMod). Izbor simulacionog jezika vrši se na osnovu nekoliko kriterijuma, od kojih značajno mesto imaju lakoća korišćenja, postojanje odgovarajućeg sistema za pronalaženje i uklanjanje grešaka, mogućnost korišćenja podataka iz drugih programa, na primer, programa za tabelarna izračunavanja i CAD paketa i mogućnost kombinacije sa grafičkim i animacionim okruženjima bez dodatnog programiranja. Još jedan bitan činilac je mogućnost kombinovanja simulacionog modela sa modelom ležišta i softverom za kratkoročno i dugoročno planiranje proizvodnje.

Paket AutoMod firme AutoSimulation Inc. zadovoljava sve navedene kriterijume. AutoMod je kombinovani sistem za modeliranje kontinualnih i diskretnih procesa. Ovaj paket pruža mogućnost brzog generisanja animiranih simulacionih modela. Implementirani CAD sistemi omogućavaju kreiranje slike modelovanog sistema. Postojanje integrisanog razvojnog okruženja i interaktivnih alatki za uklanjanje grešaka olakšava verifikaciju i validaciju modela.

AutoMod se razlikuje od ostalih simulacionih jezika po mogućnosti da fizičke elemente sistema opisuje fizičikim (grafičkim) objektima, dok se logika sistema opisuje logičkim objektima. AutoMod poseduje i napredne mogućnosti koji omogućavaju korisniku simuliranje kompleksnih sistema kretanja, kao što su roboti, alati, transportne linije i mašine za posebne namene. Sva grafika se prikazuje u trodimenzionalnom prostoru, sa, praktično, neograničenim mogućnostima vizuelne kontrole, uključujući translaciju, rotaciju, promenu veličine, perspektivu i kontinualno posmatranje kretanja.

Korišćenjem AutoMod-a, moguće je jednostavno modelirati transportne sisteme: transportere (kao što su viljuškari, kamioni ili Automatic Guided Vehicle (AGV) systems), konvejere, automatske sisteme za skladištenje, robote i mostovske dizalice. Kako bi kreirao transportni sistem, material movement systems, the user simply creates geometric entities such as paths and stations and then inputs the operating parameters such as velocity and acceleration. An AutoMod model consists of one or more systems. A system can either be a process system in which control logic is defined or materials handling system. Each model must contain one process system and may contain any number of movement systems. Loads that flow through the process logic have the ability to claim and release resources, enter or leave queues, be added to or removed from order lists, change the value of variables, counters or load attributes, create a new load or kill an existing load, read from or write to external files and determine the next process to move in. Resources can be used to represent machines, operators or other types of objects. Resources can be busy or idle and available or not. Resources can have random failures that can be represented using probability distributions. During animation, colors indicate the status of each resource and statistics are automatically collected for every resource in a model.

When applying 3D animation, the key elements of the system are represented by icons that will change shape, color, or position when there is a change of status in the simulation. Animation effectively communicates the essence of a simulation model to key personnel, thereby greatly increasing the model's credibility. There are several other potential benefits for employing animation during a simulation run. These would include assistance with model validation, assistance with debugging, and an illustration of the dynamic behavior of the system. It should be noted that animating a simulation model usually increases the duration of the run time period of a simulation run.

3. STUDY OF THE MATERIAL HANDLING SYSTEMS

The transportation system for overburden removal at Pljevlja Coal Mine is composed of several sub-systems: shovel-trucks, in-pit crushing, belt conveying and waste disposal, see Fig. 1.

Shovel-trucks subsystem: Blasted overburden is loaded by shovels (EKG 12.5 and EKG 15) into trucks (OK-95 and OK-100) and transported to the in-pit crusher. The location of the crusher is selected such that trucks largely travel horizontal routes and only a few routes uphill. Transportation distance is varying from 50 to 1.000 m.

In-pit crushing subsystem: Heavy trucks discharge the overburden into feed bin with volume of 150 m^3, from three truck discharge spots. The material is transported from the bin to the double roll crusher

korisnik kreira geometrijske objekte kojima, zatim, priključuje operativne parametre, kao što su brzina i ubrzanje. Model u AutoMod-u se sastoji od nekoliko sistema, koji mogu biti procesni, koji sadrže logiku sistema ili transportni sistemi. Svaki model mora imati bar jedan procesni sistem i proizvoljni broj transportnih sistema. Tovari koji se kreću kroz logiku procesa mogu da zauzmu ili oslobode resurse, uđu u ili izađu iz reda čekanja, budu dodati na ili uklonjeni sa liste porudžbina, menjaju vrednosti varijabli, brojača ili atributa, kreiraju novi ili unište postojeći tovar, očitavaju ili pišu u spoljašnje datoteke i da odrede sladeći proces u koji treba da uđu. Resursi mogu biti korišćeni za predstavljanje mašina, operatera, ili druge tipove objekata. Resursi mogu biti u različitim stanjima: zauzeti, slobodni, dostupni ili nedostupni (pokvareni). Zastoji resursa se modeliraju korišćenjem raspodela verovatnoće. U animaciji stanja resursa se prikazuju promenama boje, dok se svi relevantni statistički podaci prikupljaju za svaki model u sistemu.

Tokom odvijanja trodimenzionalne animacije, ključni elementi sistema su prikazani vizuelnim objektima koji menjaju oblik, veličinu, boju ili položaj pri promeni stanja. Animacija efikasno prenosi suštinu simulacionog modela ključnom osoblju, povećavajući na taj način kredibilitet modela. Ostale koristi od primene animacije su olakšana validacija modela i uklanjanje grešaka, kao ilustrovanje dinamičkog ponašanja sistema. Potrebno je naglasiti da animacija povećava vreme izvršenja simulacije.

3. STUDIJA TRANSPORTNIH SISTEMA

Transportni sistem za otkopavanje otkrivke na rudniku uglja Pljevlja je sastavljan od nekoliko podsistema, a to su: bager-kamioni, drobilice, trakasti transporteri i odlaganja (slika 1.).

Podsistem bager-kamioni: Odminirana otkrivka se utovaruje bagerima (EKG 12.5 i EKG 15) u kamione (OK-95 i OK-100) i transportuje do drobilice. Drobilica je postavljena tako da se kamioni kreću uglavnom horizontalno, uz samo nekoliko uspona. Dužina transporta varira od 50 do 1000 m.

Podsistem drobilice: Kamioni sa tri istovarna mesta istovaruju otkrivku u prijemni bunker drobilice, zapremine 150 m^3. Materijal se iz prijemnog bunkera transportuje do dvobubanjske drobilice pomoću člankastog dodavača. Pošto by apron feeder. Since the speed of feeder is adjustable, the feed to the crusher is optimized in relation to the bin fill levels. The maximum size of the feed lumps are 1.0m x 1.2m x 1.5m, is related to the feed opening of the crusher. The level of material in the feeding chute is continuously monitored, and if clogging occurs, the apron feeders are switched off. The lump material is broken by the crusher (KRUPP - 2.400 t/h) to a size of less than 300/350 mm and fed, together with the spillage from the apron feeder, to the discharge conveyor.

je brzina dodavača promenljiva, brzina hranjenja drobilice se prilagođava u zavisnosti od popunjenosti prijemnog bunkera. Maksimalna veličina komada je 1.0 x 1.2 x 1.5 m, prema veličini prijemnog otvora. Nivo materijala u bunkeru se kontinualno prati i u slučaju zaglavljivanja, isključuje se člankasti dodavač. Otkrivka se usitnjava u drobilici (KRUPP – 2.400t/h) na granulaciju materijala od 300/350mm i pretovara, zajedno sa prikupljenim materijalom koji se prosuo sa člankastog dodavača na pretovarni transporter.

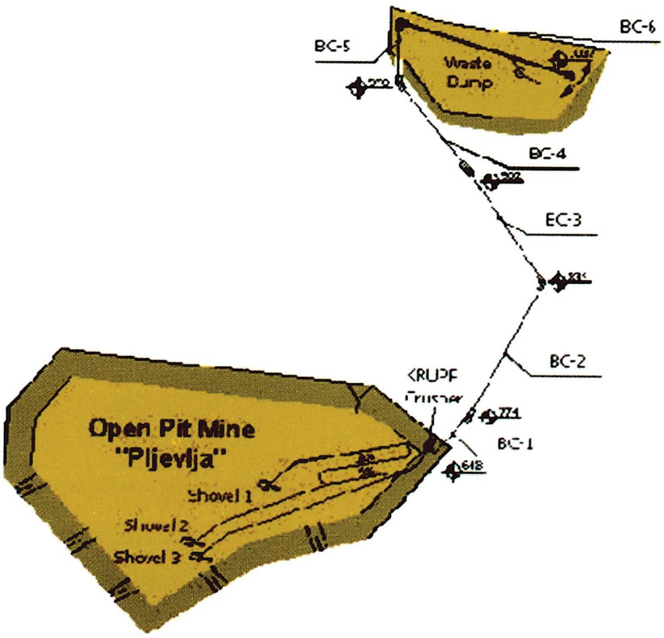


Figure 1 Material handling system at Pljevlja Coal Mine
Slika 1 Transportni sistem rudnika uglja Pljevlja

Belt conveying subsystem: The conveyor system located up-stream from the crushing plant has a belt width of 1400 mm with the belt speed of 4.5 m/s. The system comprise six individual conveyors, of which five are stationary and one (on the dump site) shiftable. The total length of six conveyors is 5124 m. All the belt conveyors have standardized parts and belt quality of EP 3150 6/2M. The conveying system transport material from the mine at an upward gradient approximately of 9^0, and lifting height of 390 m.

Podsistem trakastih transportera: Širina traka na transporterima, postavljenim iza drobiličnog postrojenja je 1400 mm, a brzina 4.5 m/s. Sistem se sastoji od 6 transportera, od kojih je 5 stacionarnih, a jedan (na odlagalištu) pomerljiv. Ukupna dužina transportera je 5124 m. Svi transporteri imjaju standardizovane dimenzije i kvalitet trake EP 3150 6/2M. Visina dizanja materijala je 390 m, a prosečan nagib 9° trase transportera.

Overburden disposal subsystem: The overburden disposal sub-system comprise the tripper car which travels over the shiftable dump conveyor and the spreader. The spreader (ARs 1400/25+30x13) is designed to discharge waste material on a 27m deep and 10m high dump with a repose angle of 40^0.

Podsistem za odlaganje otkrivke: Podsistem za odlaganje otkrivke se sastoji od pretovarnih kolica koja se kreću po nestacionarnom transporteru i odlagača. Odlagač (ARs 1400/25+30x13) ima visinu odlaganja 27m u dubinskom i 10m u visinskom radu.

During last year company planned to increase the system utilization to meet coal production demands for thermal power plant in coming years. Consequently, it was planned to analyze all the constraints in the mine transportation system and enhance the process reliability. The integrated nature of the transportation system demands that all the subsystems should function with acceptable level of reliability to achieve the planned production. If any equipment unit (or subsystem) is not working efficiently, this may reduce the efficiency of the entire transportation system. To locate the bottlenecks in the transportation chain and model their effects, a research project was initiated to analyze and model the operational reliability of the various subsystems in the transportation system.

4. DEVELOPMENT OF SIMULATION MODEL

Modeling of System Reliability

Reliability modeling and analysis is an important step in planning, design and operation of complex engineering systems and gradually being accepted as a standard tool for system analysis by most of the leading mining companies all over the world. A material handling system is defined as the combination of equipment which are interlinked by some form of regulated interactions, or in other words - a system is the collection of interacting, sub-systems. The reliability of such system depends on the reliability of its subsystems and on the configuration of the system. In an integrated mine system, the capability of the system to meet the production targets is mainly dependent on the operating availability of the system and its constituent sub-systems. The availability of the system is a function of its reliability and the maintainability. If the maintainability characteristics are assumed to be constant, the availability of the system will depend on its reliability to perform the assigned mission satisfactorily. A higher rate of availability can be expected from the system with higher reliability. On the other hand, it generally costs more money to build higher reliability into the system. Therefore, a trade-off must be done between reliability and cost. Once the optimal reliability is arrived at, this will form a basis for defining the condition of optimal system availability and subsequently the lower limits on the sub-systems availabilities.

There are many variations on the definition of the reliability to suit various circumstances. A definition considered appropriate for the mine operation system is "The reliability of a system is the probability that it will perform or operate its

Da bi se povećao kapacitet sistema na osnovu efikasnijeg korišćenja podsistema u narednom periodu rada rudnika, izvršena je simulaciona analiza radi iznalaženja svih ograničenja u sistemu i uslova za povećanje pouzdanosti rada. Integrisana priroda tansportnog sistema zahteva da svi podsistemi rade sa prihvatljivim nivoom pouzdanosti, kako bi se postigla planirana produktivnost. Ako bilo koja jedinica ili podsistem ne funkcionišu dobro, efikasnost celog sistema može biti umanjena. Da bi se odredila uska grla u transportnom sistemu, sprovedeno je istraživanje kako bi se odredila operativna pouzdanost različitih transportnih podsistema.

4. RAZVOJ SIMULACIONOG MODELA

Modeliranje pouzdanosti sistema

Modeliranje i analiza pouzdanosti su važan korak u planiranju, projektovanju i funkcionisanju složenih rudarskih sistema i postepeno su prihvaćeni od strane većine vodećih svetski rudarskih kompanija kao standardni alat za analizu sistema. Transportni sistem se može definisati kao kombinacija opreme međusobno povezane na određeni način, ili drugim rečima – sistem je skup međusobno povezanih podsistema. Pouzdanost ovakvog sistema zavisi od njegove konfiguracije i pouzdanosti komponenti sistema. Kod integrisanog rudarskog sistema, sposobnost sistema da ispuni postavljene ciljeve zavisi, uglavnom, od operativne raspoloživosti sistema i podsistema koji ga čine. Raspoloživost sistema je funkcija pouzdanosti i održavanja. Ukoliko se pretpostavi da su karakteristike održavanja konstantne raspoloživost sistema će zavisiti od pouzdanosti za obavljanje funkcije na zadovoljavajući način. Viši nivo raspoloživosti se može očekivati od sistema sa višim nivoom pouzdanosti. S druge strane, pouzdaniji sistemi su skuplji. Stoga je potrebno postići kompromis između pouzdanosti i troškova. Pošto se ostvari optimalna pouzdanost, dobija se osnova za definisanje optimalnih uslova raspoloživosti sistema.

Postoje mnoge definicije pouzdanosti načinjene za različite slučajeve. Definicija koja je odgovarajuća za rudarske sisteme je: "Pouzdanost sistema je verovatnoća da će sistem obavljati funkciju za koju je projektovan bez otkaza pod datim uslovima i tokom required function without failure under given condition for an intended operating period." Mathematically it can be expressed as:

$R(t) = 1 - Q(t)$

where:
$R(t)$ - is reliability function evaluated at time t,
$Q(t)$ -is cumulative failure distribution:

$R(t) = 1 - \int_0^t f(t)dt$, since $Q(t) = \int_0^t f(t)dt$

where $f(t)$ is failure density function. Since the total area under the density function must be unit, above equation can be written as:

$$R(t) = \int_t^\infty f(t)dt.$$

Reliability modeling and analysis is often used to determine weather a mining production process is maintaining an acceptable level of performance. The performance criteria vary widely and in the case of reliability analysis, the variable commonly used is mean-time-between-failures (MTBF) in some period of operating time. MTBF is mathematically the mean of the failure distribution of the system and can be calculated as:

$$MTBF = \int_0^\infty R(t)dt.$$

The probabilistic nature of system reliability arises from the fact that the performance parameter (which is random variable) of the system follows a pattern which may be expressed in probabilistic terms. The function which describes this pattern or distribution of the performance parameter of the system is known as the distribution function. If the particular set of performance (or failure) is well represented by a particular distribution, we conclude that the failure characteristics follow that particular distribution. The two most popular and easy to understand models are the exponential and Weibull distribution. Unfortunately, in many cases the choice of exponential distribution as a failure model is based on the fact that it is easy to apply rather than on the physical understanding of the failure characteristics dominating the life cycle characteristics of the equipment. However, for reliability evaluation of a mine transportation system, the exponential model may be more relevant due to its simplicity. The great versatility of the Weibull distribution stems from the possibility to adjust it to fit the many cases where the hazard rate either increases or decreases because this distribution has no fixed characteristic shape.

određenog perioda." Matematički, ovo se izražava:

$R(t) = 1 - Q(t)$

gde je:
$R(t)$ - funkcija pouzdanosti procenjena za vreme t,
Q(t) - kumulativna raspodela otkaza:

$R(t) = 1 - \int_0^t f(t)dt$, pa imamo $Q(t) = \int_0^t f(t)dt$

gde je f(t) funkcija gustine otkaza. Pošto ukupna površina ispod krive funkcije gustine mora biti jednaka jedinici, pa možemo pisati:

$$R(t) = \int_t^\infty f(t)dt.$$

Modeliranje i analiza pouzdanosti se, najčešće, koriste da se odredi da li proizvodni proces ima prihvatljiv nivo performansi. Kriterijum performansi varira u širokim granicama i u slučajevima analiza pouzdanosti, najčešće se koristi srednje-vreme-između-otkaza (mean-time-between-failures, MTBF), tokom određenog vremena rada. Matematički, MTBF predstavlja srednju vrednost raspodele otkaza sistema i može biti izračunata kao:

$$MTBF = \int_0^\infty R(t)dt.$$

Priroda pouzdanosti sistema je stohastička što proizilazi iz činjenice da parametar performansi (koji je slučajna promenljiva) sledi raspodelu koja može biti opisana terminima verovatnoće. Funkcija koja opisuje raspodelu parametra performansi sistema se naziva funkcija raspodele. Ako je određeni skup parametara performansi (ili otkaza) dobro opisan određenom raspodelom, tada se može zaključiti da se taj parametar ponaša po raspodeli. Dva najpoznatija i najlakša za razumevanje modela su eksponencijalna i Weibull raspodela. Nažalost, u mnogim slučajevima, izbor eksponencijalne raspodele za model otkaza je posledica lakoće njene primene, a ne poznavanja karakteristika otkaza. Međutim, pri proceni pouzdanosti rudarskih transportnih sistema, eksponencijalni model je relevantan zbog svoje jednostavnosti. Velika pouzdanost Weibull raspodele potiče od mogućnosti prilagođavanja funkcije mnogim slučajevima u kojima stopa rizika raste ili opada, pošto ova raspodela nema fiksirani oblik. Postoji

Extensive literature exists on the applicability of Weibull distribution to reliability evaluation problems.

obimna literatura o primenjivosti Weibull raspodele na probleme procene pouzdanosti.

Modeling of in-pit crushing/belt conveyor systems

Modeliranje sistema drobilica/transporteri sa trakom

There are two major choices available for constructing simulation models of bulk material conveying systems: the use of special purpose software packages and the use of discrete-event simulation languages.

A number of special purpose software packages are developed. These include CMHS [6], CMBCS [7], and BELTSIM [8], among others. Major advantages of these packages are that the user can have lower levels of simulation skills and the models can be constructed quickly. The user only needs to know how to interface with the package, specifying network topology and system operating parameters. Programming is not required, although knowledge of proper statistical procedures to analyze simulation output is certainly needed. These packages are useful for certain problems, but they also have a number of limitations:

1. most employ a discretized representation of bulk material flows that can result in slow execution and/or reduced accuracy of the generated process histories, and
2. they offer reduced flexibility in the range of systems that may be modeled relative to modeling in a general-purpose simulation language.

Simulation languages can directly overcome these difficulties. However, they require considerably more skill on the part of the analyst, since a simulation program must be written; and, for complex systems, this can be time consuming. Moreover, simulation languages focus primarily on the simulation of discrete processes, and, like most existing conveyor simulation packages, in practice one typically uses a discretized representation of bulk material flows with the attendant difficulties noted above.

It is often reasonable to assume that the derivatives of the continuous state variables in a bulk material handling system change at discrete points in time. For example, the derivative of the materials level in the crusher bunker is the difference between the inflow rate and outflow rate from the bunker. If all of the derivatives of the continuous state variables change as a discrete process, it is possible to generate time histories of the continuous variables between the points in time when the derivatives

Postoje dve mogućnosti pri kreiranju simulacionih modela sistema za kontinualni transport rasutih materijala: korišćenjem namenskih programa ili korišćenjem simulacionih jezika za modeliranje diskretnih događaja.

Postoji veći broj specijalizovanih programskih paketa. Neki od njih su CMHS [6], CMBCS [7] i BELTSIM [8], između ostalih. Osnovna prednost ovih paketa je u tome što korisnik može imati manje znanje o simulacijama, a modeli mogu biti brzo razvijeni. Korisnik mora samo da poznaje rad sa paketom, da definiše topologiju mreže i operativne parametre sistema. Programiranje nije neophodno, iako je potrebno poznavanje odgovarajućih statističkih procedura za analizu rezultata simulacije. Ovi paketi su korisni pri rešavanju određenih problema, ali poseduju neka ograničenja, i to:

1. većina koristi diskretizovanu predstavu toka rasutih materijala, što može rezultovati sporim izvršavanjem i/ili manjom tačnošću i
2. fleksibilnost u modeliranju različitih sistema je redukovana u odnosu na simulacione jezike opšte namene.

Simulacioni jezici prevazilaze ove teškoće, ali je za njihovo korišćenje potrebno mnogo veće znanje, pošto simulacioni program mora biti napisan, a to kod složenih sistema može zahtevati mnogo vremena. Osim toga, većina postojećih simulacionih paketa je primarno usmerena na simuliranje diskretnih sisitema, dok za kontinualni transport koriste diskretizovani prikaz toka rasutih materijala.

Najčešće se pretpostavlja da se izvodi kontinualnih promenljivih u sistemima za tansport rasutih materijala menjaju u diskretnim vremenskim intervalima. Na primer, nivo materijala u bunkeru drobilice je razlika između ulaza i izlaza. Ako se izvodi svih varijabli kontinualnog stanja menjaju kao diskretni procesi, moguće je formirati istorije vrednosti kontinualnih varijabli između tačaka u kojima se menjaju izvodi analitičkom integracijom. Jednostavno, polinomi daju vrednosti kontinualnih varijabli između tačaka u kojima se change by analytical integration. Simple, polynomial expressions give the value of the continuous variables for points in time between derivative changes. The points in time that the derivatives change are dictated by process logic, e.g., in a in-pit crushing system at the point in time the bunker becomes full the incoming trucks must wait for unloading. Given the analytical expressions for the continuous variables, these points in time can be determined by root finding. As explained in [8], the assumption that the derivatives change as a discrete process can be used to simulate bulk conveying systems using the event-scheduling approach to structuring discrete-event simulation models. This modeling approach results in both higher execution speed and greater simulation accuracy than discretization approaches discussed in the earlier section.

Simulation modeling of mine operations in AutoMod

To provide the most accurate representation of the real system performance, an actual mine production data profile was used as the input to the simulation where possible. Below are the used input data sets:

Shift information: This includes the shift timetable, the time lost in shift preparation, the organizational delays per day and other scheduled delays.

Shovel/trucks operations: The base case used as a reference for this study has the following features:

- 3 shovels with bucket capacity of 15m^3; 2400 tph +/- 200 tph
- 3 truck types; 100, 136 and 150 tonnes
- Trucks are subject to 90 minutes of breaks (driver breaks, lunch, fueling, shift changes, etc.) of various kinds per 12 hour shift.
- Shovels move (and do not load) for 10 minutes after every 10,000 tonnes loaded.
- If an unscheduled down for a shovel is less than 30 minutes, the trucks are not released.
- Shovels and trucks are subject to unscheduled failures. Their respective distribution functions were determined using UniFit II statistical simulation software. According to the chi-square and K-S goodness-of-fit test, mostly two distributions, the Weibull and the Gamma were found to describe the mean-time-between-failures (MTBF) and the mean-time-of-repair (MTR), which are based on actual measurements, see figure 2.

menjaju izvodi. Tačke u vremenu u kojima se menjaju izvodi su određene logikom procesa, na primer, u slučaju drobilice, kada se bunker napuni, kamioni moraju da čekaju na istovar. Ako su dati analitički izrazi kontinualnih varijabli, ove tačke u vremenu mogu biti određene integraljenjem. Ako se, kao što je navedeno u [8], usvoji pretpostavka da se izvodi menjaju kao diskretne promenljive, tada transport rasutih materijala može biti modelovan korišćenjem "event-scheduling" pristupa za formiranje strukture diskretnih modela. Ovakav pristup modeliranju rezultuje većom brzinom izvršenja i većom preciznošću nego diskretizacioni pristup dat u prethodnom poglavlju.

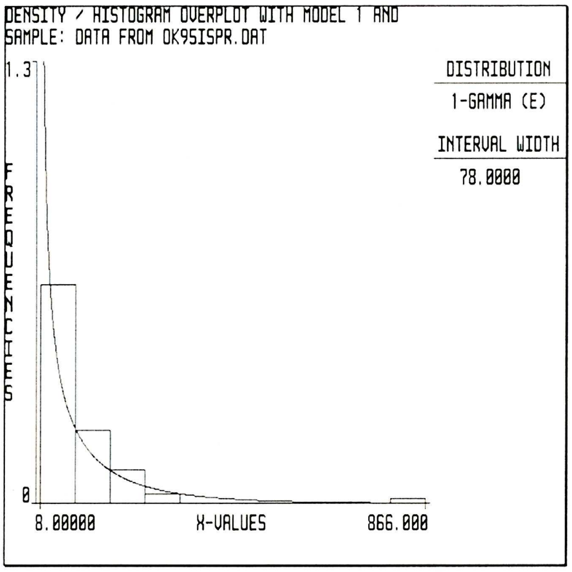
Simulaciono modeliranje rudarskih operacija u AutoMod-u

Kako bi se ostvario najtačniji prikaz performansi realnog sistema, korišćeni su stvarni podaci sa rudnika kao ulaz, kad god je to bilo moguće. Ovde su dati ulazni setovi podataka:

Informacije o smenama: Pod ovim informacijama se podrazumeva raspored smena, vreme izgubljeno u pripremama za smene, dnevni organizacioni zastoji i ostali predviđeni zastoji.

Rad bagera/kamiona: Osnovni podaci koji su korišćeni kao referenca za ovu studiju su:

- 3 bagera zapremine kašike 15m^3; 2400 tph +/- 200 tph
- 3 tipa kamiona; 100, 136 and 150 tonnes
- Kamioni su, tokom dvanaestočasovne smene, 90 minuta na različitim pauzama (pauza, ručak, dosipanje goriva, promena smene, itd.).
- Bageri se pomeraju (i ne utovaruju) tokom svakih 10 minuta posle utovarenih 10,000 tona.
- Ako je nepredviđeni zastoj bagera kraći od 30 minuta, kamioni se ne dodeljuju drugim bagerima.
- Bageri i kamioni imaju nepredviđene zastoje. Funkcije raspodele su određene korišćenjem programa za statističku analizu UniFit II. Prema chi-square i K-S testovima fitovanja, utvrđeno je da Weibull i Gamma raspodele najbolje opisuju srednje vreme između otkaza (mean-time-between-failures, MTBF) i srednje vreme opravki (mean-time-of-repair, MTR), koji su zasnovani na stvarnim merenjima, slika 2.



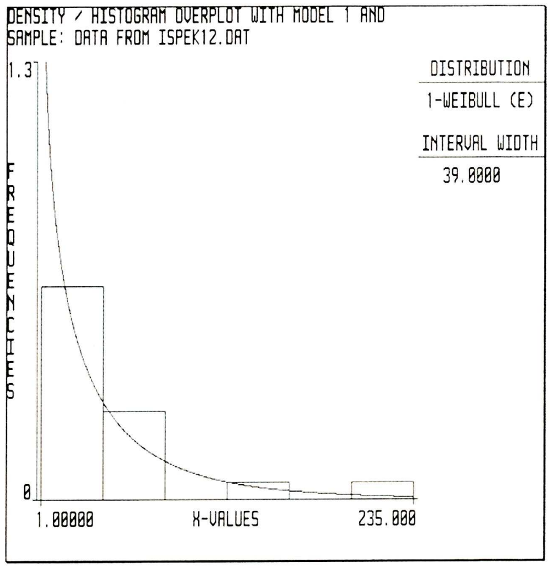


Figure 2. Distribution of MTBF for truck OK-100 and shovel EKG-15
Slika 2. Raspodela srednjeg vremena između otkaza za kamion OK-100 i bager EKG-15

- The truck travel times from the shovels to the crusher are generated from triangular distribution as function of road conditions.
- The number of trucks allocated to a shovel is a function of the shovel rate, truck size, travel times, and unload time. Trucks are dedicated to their shovel.
- The normal distribution was used to describe the loading and dumping times of the trucks.

In-pit crushing/belt conveying operations: The higher order discrete approach discussed above have been used in simulating the in-pit crushing/belt conveyor system. The interface between the in-pit crushing model and the conveyor network is accomplished by facilities built into the event routines. Unloading of trucks to the bunker initiates startup of the feeding apron and material outflow to the crusher. Material flow on the conveyors and disposal system was simulated using the event routines. Also, code was written to schedule random failures and repair times of the belts and to control startup and shutdown sequencing when these events occurred. The other relevant futures are:

- KRUPP crusher; 2400 tph +/- 200 tph
- 6 belt conveyors; 4500 tph +/- 300 tph
- Crusher hopper of 150 m^3 capacity with 3 unloading spots. If the all spots are occupied at the crusher, the trucks must wait.
- The data for the times between the failures and the times to repair crushing/belt conveying subsystem were described by the exponential distribution.

- Vreme kretanja kamiona od bagera do drobilice je generisano trougaonom raspodelom u funkciji stanja puta.
- Broj kamiona koji opslužuju određeni bager određen je u funkciji kapaciteta bagera, veličine kamiona, vremena kretanja i vremena istovara. Kamioni su dodeljeni bagerima.
- Za opisivanje vremena utovara i istovara je korišćena normalna raspodela.

Rad drobilice/trakastih transportera: U simuliranju sistema drobilica/trakasti transporteri korišćen je diskretizacioni pristup višeg reda. Veza između modela drobilice i sistema transportera sa trakom je ostvarena pomoću rutina događaja. Istovar kamiona u prijemni bunker drobilice inicira rad člankastog dodavača i materijal ulazi u drobilicu. Tok materijala na transporterima i odlagaču je simuliran korišćenjam implementiranih svojstava objekata. Kako bi se simulirali otkazi, opravke i sekvence zaustavljanja i pokretanja transportera u ovim slučajevima, napisane su posebne procedure. Ostali relevantni podaci su:

- drobilica KRUPP; 2400 tph +/- 200 tph,
- 6 trakastih transportera; 4500 tph +/- 300 tph,
- prijemni bunker drobilice kapaciteta 150 m^3 sa 3 istovarna mesta. Ako su sva istovarna mesta zauzeta, kamioni moraju čekati.
- vreme između otkaza i vreme trajanja opravke su opisani eksponancijalnom raspodelom.

Overburden disposal: This incorporates the dimensions and sizes of the dumping sites, time of moving stacker and shiftable belt conveyor, distribution for the mean time between failures, and mean time to repair.

Analysis of simulation results: This facilitates the selection of the data related to the simulation duration, the number of simulation runs, as well as the number of days to be simulated. From the simulation runs the following output can be obtained:

- Production volume (shift, daily and cumulative).
- Individual subsystems and the total system availability.
- Time lost due to individual disturbances on a day-to-day basis, and
- Cumulative number of the individual disturbances and the corresponding total time lost for the period of simulation.

Validation of the model: The model was validated using the techniques discussed by [9] in close cooperation with the mine planning engineers. Validation in simulation modeling is a process of determining (and adjusting the model) how close the model will duplicate actual operational results with actual operating conditions as input to the model. The animation model also was used in validation phases to visually observe dynamic activities in transportation process, examine the logic and the assumptions of a simulation model. During the verification and validation process, some small changes were made in the model to bring it closer to the reality. At Pljevlja Coal mine, the simulation model results for a truck-shovel/in-pit crushing/conveyors model were different from the actual operating results by less than 2%. Sufficient detail was included in the model to permit this accuracy to be attained.

5. 3D ANIMATION OF THE MINE OPERATIONS IN AUTOMOD

The AutoMod simulation environment includes a three dimensional CAD module. All of the objects can be a combination of basic solid forms such as polygons, cylinders and blocks. In order to build a three dimensional representation of the mine operations, the layout must be constructed around the material handling system. The possibility of graphically representing the advancement of the shovel (or stacker) during the advancement cycle in a open pit not straightforward since the graphics

Odlaganje otkrivke: Ovde su uzete u obzir dimenzije odlagališta, vreme premeštanja odlagača i pomerljivog transportera, raspodela za srednje vreme između otkaza i srednje vreme opravke.

Analiza rezultata simulacije: Ovo olakšava izbor podataka koji se odnose na trajanje simulacije, broj replikacija simulacionog eksperimenta, kao i broj dana koji se simuliraju. Ponavljanjem simulacije moguće je dobiti sledeće podatke:

- Ostvarenu proizvodnju (smensku, dnevnu i kumulativnu).
- Raspoloživost sistema i podsistema.
- Vreme zastoja po smenama i
- Kumulativni broj zastoja i ukupno vreme zastoja tokom simuliranog perioda.

Validacija modela: Validacija modela je obavljena tehnikom opisanom u [9] i u bliskoj saradnji sa inženjerima koji su radili na planiranju rudnika. Validacija simulacionog modela je proces određivanja (i prilagođavanja modela) u kojoj meri će model duplicirati stvarne operativne rezultate, ako se kao ulaz unesu stvarni operativni uslovi. Animacija se, takođe, koristi za validaciju i vizuelno uočavanje dinamičkih aktivnosti u transportnom procesu, ispitivanje logike i pretpostavki simulacionog modela. Tokom procesa validacije i verifikacije, načinjeno je nekoliko manjih izmena, kako bi se dobilo na realističnosti modela. U slučaju rudnika uglja Pljevlja, rezultati simulacionog modela bager/kamion/drobilica/trakasti transporteri su se razlikovali od stvarnih operativnih rezultata za manje od 2%. U model je uključeno dovoljno detalja, kako bi se postigao ovaj nivo pouzdanosti.

5. TRODIMENZIONALNA ANIMACIJA RUDARSKIH OPERACIJA U AUTOMOD-U

U simulacioni paket AutoMod uključen je CAD modul za trodimenzionalnu grafiku. Svi objekti mogu biti prikazani kombinovanjem osnovnih oblika solida kao što su poligoni, cilindri i blokovi. Kako bi se napravio trodimenzionalni prikaz rudarskih operacija, odgovarajući objekti se pozicioniranju preko transportnog sistema. Grafički prikaz napredovanja bagera (ili odlagača) nije jednostavan, i zahteva pisanje posebnog koda, pošto se grafički prikaz have to be updated and modified as the simulation advances in time, figure 3.

objekata mora osvežavati i modifikovati sa odvijanjem simulacije, slika 3.

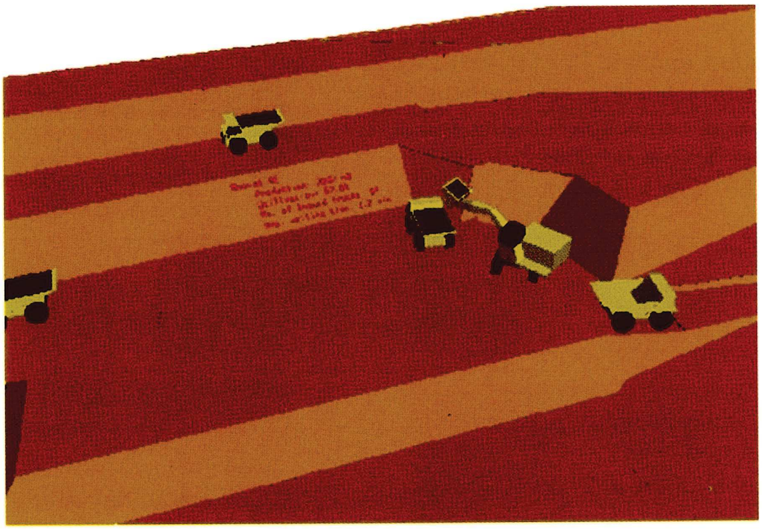


Figure 3 Loading by shovel EKG-12
Slika 3 Utovar bagerom EKG-12

Every piece of equipment is graphically represented by a scaled drawing/icon having the dimensions and size specifications of real mining equipment. To simulate truck motion in a layout AutoMod includes a track element. A track must be incorporated in the simulation to guide a truck along its path of travel. The tracks can be bi-directional, thus allowing equipment to travel in both directions and orientations (driving forward or backward in both directions) see figure 4 .

Sva oprema je grafički prikazana u razmeri, modelom čije dimenzije i odgovaraju dimenzijama stvarne mašine. Za simuliranje kretanja kamiona koriste se putanje koje "vode" kamion po trasi. Putanje mogu biti dvosmerne, tako omogućavajući kretanje kamiona u oba smera (kretanje napred i nazad u oba smera), slika 4.

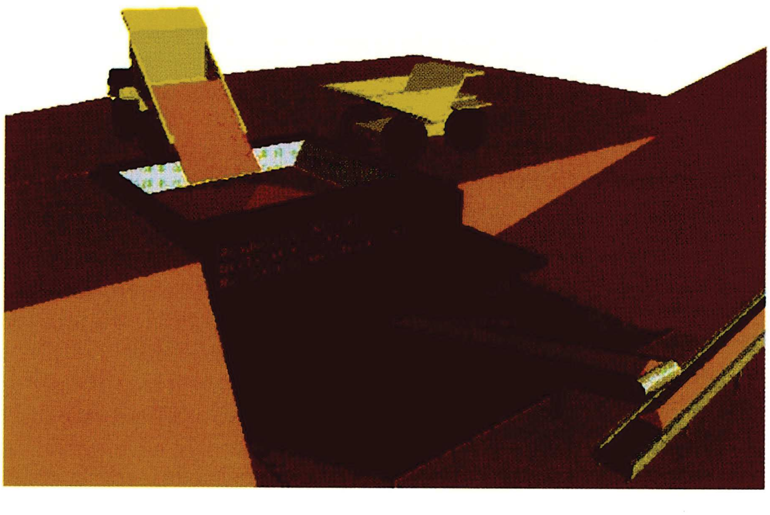


Figure 4 Dumping into crusher bunker
Slika 4 Istovar u bunker drobilice

When an AutoMod model runs, the simulation logic and physical animation run concurrently with all graphics being represented in three dimensions. The user has the ability to change the view of the model as it is running, zoom, pan, or rotate the 3-D world.

6. COMMENTS ON SIMULATION RESULTS

AutoMod simulation model was used to study the material flow and associated assumptions from the beginning to the end of the transportation system. Simulation model was run for a period of 90 days (2160 hours), which is the same duration time for which actual data were collected.

Study of truck fleet: What is the right number of trucks to use? Matching the truck size to the shovel is very important, as well as the maximum operating rate of the equipment. Figure 5 shows how the average daily production of the system changes as the number of trucks in the fleet changes. This information must be combined with other operating considerations, capital and operating costs, and maintenance practices to determine the right number of trucks to have in the fleet.

Po startovanju modela u AutoMod-u simulaciona logika i fizička animacija se odvijaju istovremeno. Grafički prikaz je trodimenzionalan, a korisnik ima mogućnost promene položaja kamere tokom odvijanja simulacije. Takođe, korisnik može menjati položaj tačke gledanja tokom izvršenja simulacije, da uveličava detalje, da pomera i rotira čitav trodimenzionalni prikaz.

6. KOMENTARI REZULTATA SIMULACIJE

Simulacioni model u AutoMod-u je korišćen kako bi se prikazao tok materijala i proverile određene pretpostavke u transportnom sistemu. Simulacioni eksperiment je izvršavan za 90 dana, odnosno 2160 sati, što odgovara vremenu u kom su prikupljani podaci iz stvarnog sistema.

Analiza veličine voznog parka: Koliko kamiona treba koristiti? Kako uskladiti kapacitet kamiona i bagera. Na slici 5 se vidi kako se dnevna proizvodnje sistema menja u zavisnosti od broja kamiona u sistemu. Ovaj podatak se kombinuje sa drugim operativnim razmatranjima, kapitalnim troškovima i troškovima rada, kao i sa održavanjem, kako bi se odredila odgovarajuća veličina voznog parka.

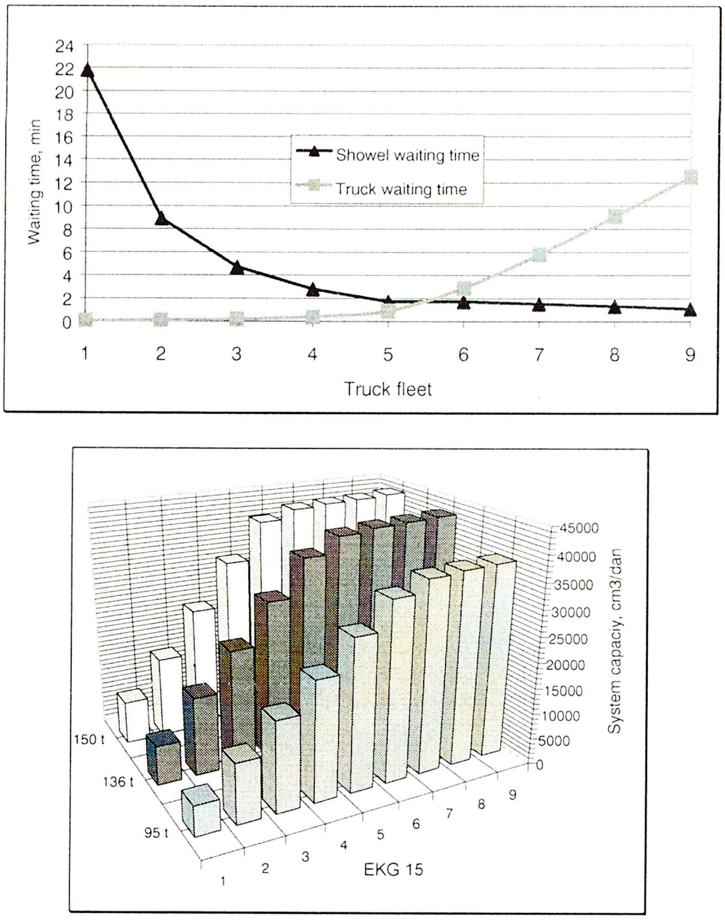


Figure 5. Determining right truck fleet size
Slika 5 Određivanje veličine voznog parka

Study of reliability: Study of the operating reliability of transportation system is shown in Table 1. Results include the total time (in minutes) that each subsystem was operational, or down times for repairs. The total system availability was 60%. This has helped to identify the factors that are more sensitive to subsystem availability. One of them was the reliability of the in-pit crushing unit that greatly influences the mine production volume. Than, the simulation model was used to analyze and quantify the effect of increasing the reliability of in-pit crushing subsystem on total mine production. Figure 6 shows the trend of mine production as the crushing unit reliability increase.

Analiza pouzdanosti: Studija operativne pouzdanosti transportnih sistema je data u Tabeli 1. Rezultati uključuju ukupno vreme (u minutima) tokom koga je svaki podsistem bio raspoloživ, ili u otkazu. Ukupna raspoloživost sistema je 60% Ovo je pomoglo da se uoče faktori koji su uticali na raspoloživost podsistema. Jedan od njih je i pouzdanost drobilice, koja u velikoj meri utiče na obim proizvodnje rudnika. Simulacioni model je potom korišćen da se analiziraju i kvantifikuju efekti povećanja pouzdanosti podsistema drobilice na ukupnu proizvodnju. Slika 6 pokazuje varaijacije u proizvodnji sa porastom pouzdanosti drobilice.

Table 1 Simulation results of the system operating reliability
Tabela 1 Rezultati radne raspoloživosti sistema

Subsystem	Simulation data		Actual data	
	MTR	Availability	MTR	Availability
Shovel-trucks	231	89%	282	87%
In-pit crushing	451	79%	551	74%
Belt conveying	199	91%	150	93%
Waste disposal	111	94%	71	97%

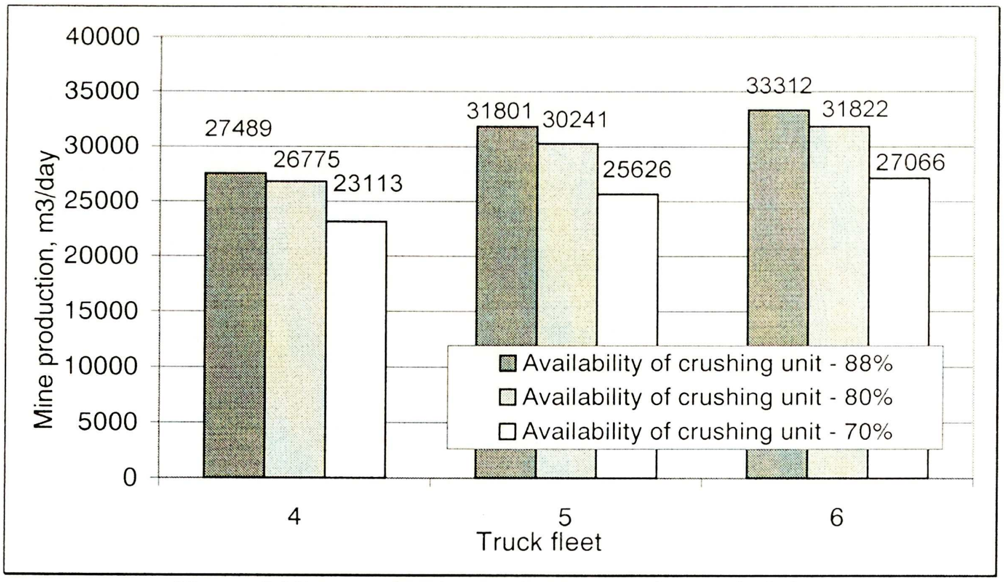


Figure 6 Mine production and in-pit crushing reliability
Slika. 6 Proizvodnja i pouzdanost drobilice

Study of hopper size: The base case assumes a hopper size of 150 m^3. Figure 7 shows the impact of hopper size on average daily system production. It would appear that the larger hopper size has some value, but no significant change was obtained when the maximum capacity of the hopper was increased up to 250 m^3.

Analiza veličine prijemnog bunkera drobilice: Osnovni slučaj podrazumeva zampreminu prijemnog bunkera drobilice od 150 m^3. Slika 7 prikazuje uticaj veličine prijemnog bunkera na dnevnu proizvodnju. Pretpostavljalo se da će veličina prijemnog bunkera uticati na kapacitet, ali se tokom analize pokazalo da povećanje zapremine prijemnog bunkera na 250 m^3 ne utiče u značajnoj meri na kapacitet sistema.

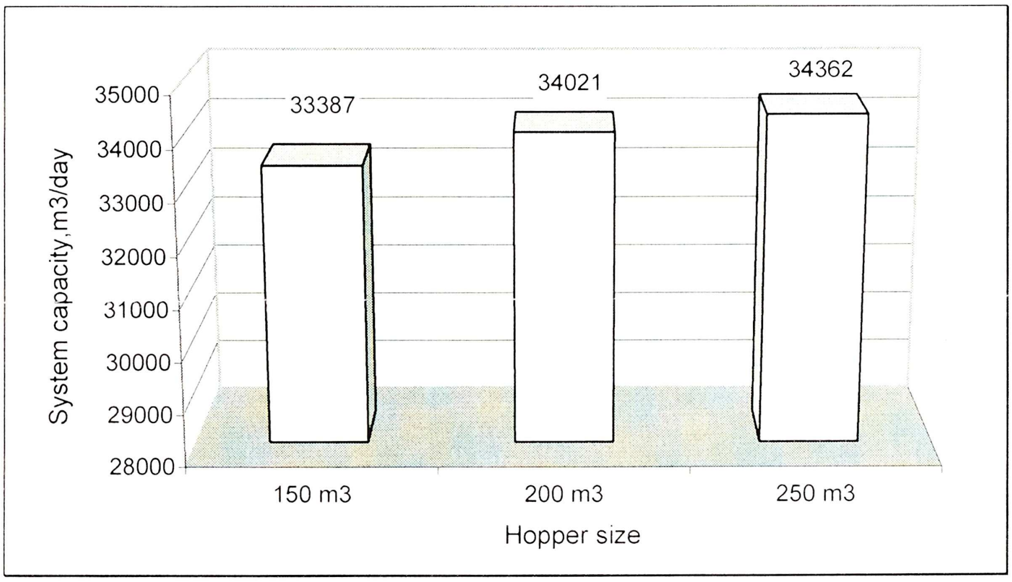


Figure 7 Influence of hopper size on system capacity
Slika 7 Uticaj zapremine bunkera na kapacitet sistema

7. CONCLUSIONS

Computer simulation is a time-tested, powerful decision support tool that can improve the analyses of production systems and reduce the uncertainty and risk associated with changes to the system. Today advances and improvements in simulation tools have made this a compelling technology for competing in today's highly competitive global market.

Presented case study in this paper is example of how changes to the mine material handling system can be evaluated and tested before implementation. It is clearly evident that the power of simulation must not be underestimated. To scientifically quantify possible changes to a system is now even more important than ever. When capital investments must be made to improve productivity the benefits must be realized and simulating the system and possible alternatives is the only way to quantify whether all expectations will be met.

7. ZAKLJUČCI

Kompjuterska simulacija je moćna metoda u procesu odlučivanja, koja je izdržala probu vremena i koja može poboljšati analizu proizvodnih sistema i redukovati nesigurnost i rizik vezan za promene u sistemu. Današnji napredni simulacioni alati čine ovu metodu konkurentnom na današnjem, veoma dinamičnom globalnom tržištu.

Simulaciona analiza prikazana u ovom radu je jedan od primera kako se izmene u transportnom sistemu mogu ocenjivati i testirati pre primene. Jasno je da se mogućnosti koje pruža simulacija ne smeju potcenjivati. Procenjivanje mogućih promena sistema na naučnoj osnovi je danas važnije nego ikad. Kada se planiraju kapitalna ulaganja u povećanje proizvodnje potrebno je definisati pozitivne efekte, a simuliranje sistema i mogućih varijanti proizvodnje je jedini način da se odredi da li će očekivanja biti ispunjena.

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