A Simulation and Animation Model for an Asphalt Operation: Implications for Organisational Ergonomics

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A discrete simulation and animation model was created to illustrate the cycle involved when obtaining, transporting and then laying asphalt for a typical roadworks operation. These models were created using the software GPSS/H \textsuperscript{®} for the simulation and PROOF PROFESSIONAL \textsuperscript{®} for the animation. Data was obtained from an actual asphalt operation. The simulation can be used to study bottlenecks, determine how many trucks should be used on a daily basis, consider an array of productivity outputs, and answer other such “What if?” questions that may arise in typical asphalt operations. Possible applications to organisational ergonomics are discussed.

Practitioner Summary: The application of simulation and animation in civil construction roadworks may help leverage worker engagement, facilitate individual and collective learning and development, contribute to productivity planning in project management, and provide a fundamental platform for organisational ergonomics.

Keywords: Organisational Ergonomics, Simulation / Animation, Civil Construction

1. Introduction

1.1 Simulation Models in General

The GPSS/H (General Purpose Simulation System) computer programming language is a special language that is used primarily to simulate what can be classified as discrete systems. A discrete system is one where, at any given instant, a countable number of events can take place. For example, people entering a store, drivers travelling through a drive-through eatery, a truck being loaded with asphalt, a truck dumping asphalt, or a truck being washed. At any one instant, the number of events taking place can be counted. The events may vary in time according to random chance or probability of occurrence – this refers to stochastic systems which are associated with queuing theory. A truck may arrive at a site for load pick-up and then random events may occur – the truck may need to wait until a plant provides clearance for pick-up, the driver may take extra time to cover the load with a tarp or need to pause and speak with an operator and take a different amount of time to move through a plant than the next truck. Many complex engineering systems are ideal examples of discrete systems with stochastic probability as is the study of asphalt trucks being loaded and cycling to where they unload for civil roadworks projects.

The classic problem of trucks working in a surface mine site with a single shovel is one that has quite a history. Civil and Mining Engineers have been trying to solve this problem using classical means for many years. In this case, there are (n)-trucks at the site and a single shovel which can load only one truck at a time. The loaded trucks travel to a single dump area where they dump their loads and return to the shovel. Since the shovel can load only one truck at a time, an arriving truck sometimes must wait in a queue until the shovel is free. The “problem” is to determine the production of the system as the number of trucks increases. For constant load, dump and haul times, the solution is trivial, but for stochastic times, the problem can be solved for the general case only by simulation. In fact, this problem is easily solved in only a few lines of computer code using the software used here. The case where all times (travel, loading, dumping) are sampled from the exponential distribution was solved for a truck-shovel system example by Griffis (1968). Maher and Cabrera (1975) expanded on this solution for construction problems.

The GPSS/H simulation language is excellent for simulating systems that have this type of queueing. It is very easy to model a great variety of complicated systems using GPSS/H. Schriber (1974 and 1991) describe the simulation language. Sturgul (2000) gives numerous simulated examples of projects of interest to the mining engineer.
1.1.1 Basic Definitions to Describe Discrete Simulation Models

The following definitions may help readers understand the simulation modelling concepts applied to this project:

- **Modelling**: To build a model that replicates a system
- **Simulation**: To observe and test the dynamic “What-if’s?” of events that occur within a system
- **Animation**: Dynamic graphics or illustration that aids mental schemata for quick interpretation of data – considered more meaningful for scene-building and easier to interpret than data code on a page
- **Discrete system**: one in which, at any given moment, a countable number of events may occur
- **Stochastic**: Random probability
- **Queuing theory**: Mathematical study of bottlenecks or events that may involve waiting times and lines

1.2 Organisational Ergonomics

Organisational ergonomics is emerging as a paradigm that translates the impact of ergonomics into business performance, leadership, and productivity. Organisational ergonomics is defined by the International Ergonomics Association as a domain of ergonomics that is (IEA, 2015):

> “… concerned with the optimization of sociotechnical systems, including their organizational structures, policies, and processes (… communication, crew resource management, work design, design of working times, teamwork, …. and quality management).

Helander (1997) describes a survey of professional societies federated in the International Ergonomics Association that identified methods to change work organisation and design and organisational design among the five most important emerging areas in ergonomics:

1. Methodology to change work organisation and design
2. Work-related musculoskeletal disorders
3. Usability testing for consumer electronic goods
4. Human computer interface and software
5. Organisational design and psychosocial work organisation

In order to stimulate uptake and buy-in of ergonomics the productivity impact must be made transparent to business managers. In this way, the program may be considered integral to leadership systems as part of a company’s sustainable competitive advantage and essential business strategy. These efforts will help move the perception and association of ergonomics from one that is related purely to a legislative framework of safety system compliance, in response to which we may hear company managers groan, to one that is seen as market-savvy, solution-oriented, and competitive, yet still achieves outcomes of positive health for workers (Dul and Neumann, 2009).

To best support an effective organisational ergonomics program, Carayon and Smith (2000) urge practitioners to consider methods to implement participation, engagement, and learning at an individual and collective (team or organisational) level for optimum performance.

1.2.1 Adaptive Safety Management

Adaptive safety management is an emerging term that describes collective safety culture or “safety in action” (Nascimento et al, 2015). It combines safety required of regulatory compliance and the fluid interpretation of these safety requirements, including the risk taking that occurs in the coal face among workers. Effective adaptive safety management systems recognise the human factors – variability of random actions, behaviours, and events with ad-hoc procedures constructed spontaneously to adapt to the real-life scenarios of work (Nascimento et al, 2015).

Adaptive safety recognises discrepancies between safety rules and practice and works on developing the means for workers to judge when and how to adapt these rules to situations that they face. In this regard, rules are “constructs” rather than “mandates”. Procedures cannot guarantee safety and safe work.
performance is truly achieved when people apply substantive, skilful decision making and judgement about how and when to adapt procedures to the circumstance. To achieve high-safety performance, the organisation must invest in methods to develop ways to involve people in a collective understanding of system events and make sound decisions for flexible adaptation of when and how to run a risk and provide procedures as resources for action (Dekker, 2003).

The United States Depart of Energy Human Performance Improvement Handbook (2009) describes the development of integrated safety management in which events are learnings rather than failings. They outline tenets for high-reliability organisations and human performance improvement and these include recognition of excellence, the study of success – or reliability, acceptance of responsibility for one’s own safety and also the safety of others, systemic review of operational weakness and control intervention; and a drive for continuous learning and improvement that is part of the cultural norm. They view human performance as an output of behaviour and results. Questionable behaviour may result in high performance, and poor results may occur even with compliant behaviour. As such, adaptive thinking and work method is critical to quality outcomes. This is consistent with the premise of Rasmussen’s human performance classification in three levels (Rasmussen, 1983):

1. **Skill-based**: stored patterns of pre-programmed instructions
2. **Rule-based**: familiar problems are addressed by application of stored rules
3. **Knowledge-based**: novel situations in which actions must be planned, using conscious analytic processes and stored knowledge

### 1.2.2 Safety Systems in Road Construction

The Australian road construction industry is one of the highest risk industries for fatalities and serious workers’ compensation claims (Safe Work Australia, 2013 and 2015). The work occurs in an outdoor environment, around traffic, among heavy mobile plant and heavy tools generally, with variable shift-work requirements for night or day activity, and long-duration work shifts, among a culture recognised to be accepting of risk-taking (Safe Work Australia, 2014).

It is a highly regulated industry in which operational events occur under a firm hierarchical reporting structure with work teams typically inclusive of a contracting manager, project manager, engineer(s), site supervisor, site foreman, team leader, and work crew comprising of a job truck operator, mobile plant equipment operators, and labourers (to shovel, rake, sweep, or use tools to compact or break up asphalt, or dip and measure asphalt mat thickness). These teams will have lateral reporting lines to safety or environmental advisors, also.

Skills-based performance may include fundamental labouring tasks – shovelling or raking, for example. Rules-based performance may involve the interpretation of findings with a standard action or response and, in asphalt, this may involve the interpretation of readings of asphalt mat thickness and adjusting the paver speed accordingly. Knowledge-based performance requires fundamental knowledge of processes and systems to evoke spontaneous decision-making. Common problem solving events in asphalt roadworks may include conflict resolution among work teams, with principal contractors, or with members of the public; contributing to equipment or process design; interpreting procedure for an injury or medical treatment event; performing a calculation to adjust productivity output in light of a change in weather events; project planning; conducting gap analysis or root cause analysis; hosting meetings or toolbox sessions to address an area for improvement, or similar. While the majority of knowledge-based tasks are required of site supervisors and project managers, the field crew must operate and live with decisions made in the heat of the moment.

Roadworks construction is a classic illustration of the high-risk organisation described by Nascimento et al (2015) in which operations are confronted with complexity and high economic and safety stakes related to multiple trade-off decisions and arbitrage, or risk-benefit decision making. While decisions are made spontaneously by workers in the front end, management must bear the load of any trade-off, and thus accept the weight that bears structural support to the articulation of regulated safety and managed - adaptive or integrated - safety (Daniellou et al, 2011; and Nascimiento et al, 2015).

### 2. Method of Approach

#### 2.1 Rationale
The design of a discrete simulation and animation model involves the participation and consultation of stakeholders at all levels to interpret a system and consider a range of probable events and applications to test “What-if?” questions for simulation. The animation is recognised as a method to support understanding and interpretation of this data. It provides the modeller with a visual representation of the system and ensures that the simulation is correct (Sturgul, 2015). As such, the development, introduction, and trial of a discrete simulation and animation model was selected as a method to facilitate participation and adaptive learning in a roadworks construction operation and thus support resilience engineering processes in the business. Also, there was interest to consider whether the findings could impact productivity planning for project managers.

2.2 Enlisting Management Support

To embark on a project of this magnitude where resource must be allocated in untested, non-routine work activity, a strong backing by management is required. The “sell” to management is of difficult nature when there is little to benchmark or reference in terms of discrete simulation and animation with application to the road construction industry. Many of the managers within the host organisation were familiar with deterministic simulation models applied to large operations where time-studies were clocked with real-time continual feed technology in central plant operations. However, this project involved a smaller mobile plant operation with a completely different paradigm – random probabilities rather than deterministic algorithms where input “X” plus “Y” will always be equal to “Z”.

Some of the trust and support was enlisted among contracting managers owing to solid in-house business relationships and past performance of successful programs. However, the project required a project manager willing to afford extra time for the sake of learning without a vested interest or guarantee of any reward or given outcome. Another factor to help “sell” this program was the lack of upfront capital outlay for investment – the principal investigator and simulation designer were interested in this project for pedagogical learning and donated extra time and resource to test if it may have relevance to industry.

2.3 Analyse hierarchical task steps

2.3.1 Data Collection and Development

The preliminary design steps have involved:

1. Information sharing: introduction of the terminology associated with discrete simulation, sharing of literature describing similar projects, and case examples from other industries: mining, manufacturing, retail barber shops, and take-away restaurant chains, for example.
2. Management meetings among operations, safety, and quality teams to introduce this concept and discuss areas for application.
3. Individual meetings with project managers to query their level of interest to trial a project, confirm an accessible location, and determine a timeline for implementation.
4. On-site consultation, observation, and conversation with asphalt road crew to better understand workflow tasks.
5. Repeat on-site visits, interviews, and validation of findings. This included time studies to better understand discrete event occurrences – e.g. how long did it take a number of trucks to stop beneath a bin and receive their asphalt load?
6. Analysis of the system to clarify the goal of daily work activities in terms of quantity, cost, quality, and human activity.
7. Analysis of the task in terms of discrete events, queuing, and bottlenecks.
8. Multiple meetings, remote email and phone communication with the simulation expert designer.

2.3.2 The Asphalt Model

The system that was modelled consisted of the following operational considerations:

Truck Operator tasks include:

Once only:
1. Attend a site induction including the overview of the vehicle movement plan (VMP). This is completed on-site and generally takes about half an hour. The asphalt cartage suppliers generally remain consistent.

A number of different trucks are assigned to haul asphalt for the day. These are user supplied inputs for the simulation program and can vary from day to day.

Each visit the tasks include:

1. Approach Site.
2. Call plant operator on ultra-high frequency (UHF) radio communication to confirm loading time, and determine whether the vehicle needs to go to the stacking area or if it can travel directly to be filled.
3. If able to be filled, the truck approaches the lubrication stand and stops. The driver alights the vehicle and climbs the lubrication stand to access a hose and spray lubricant in the tipper.
4. The driver descends the stand and returns to the truck, and drives under the bin to be filled with asphalt product mix. There is always asphalt available for loading.
5. The truck driver either:
   a. Covers the load with their tarp, or
   b. A small percentage will travel to a separate sampling stand to await lab tech sampling. This can be an input variable. Lab sampling is generally taken for two trucks (two samples) for jobs that require < 500T of asphalt and four trucks (four samples) for ≥ 500T. The first sample represents the first 40% and the second sample represents the final 40% of production. A single production lot is 500 tonne and exceeding 500 tonne production repeats the process.
6. All trucks are weighed at a weigh bridge – the operator drives their truck over a moveable weighbridge ramp to await automated weight calculation.
7. As this is a mobile plant without the technology of pneumatic tube automation for document exchange, truck drivers must park their vehicle and walk to the asphalt plant operation tower to receive and sign their asphalt cartage docket. A vehicle movement plan (VMP) is handed to the truck driver each shift when they collect their first asphalt docket.
8. The truck driver returns to his/her truck and drives to the site to deliver the load.
9. The truck driver arrives on site and calls ahead to the site supervisor or team leader on UHF radio communications to determine if his/her load is required for immediate delivery and dump, or if he/she needs to wait at site until needed.
10. The mud-flaps are lifted and tarp opened/released for tipping.
11. Once delivery is required, the truck travels to the paver and tips their load into the hopper of the paver while slowly being pushed along by the paver during operation (OR Shuttle-buggy where required).
12. Once completed, the truck driver lowers the body, moves away to a clean-up area where they raise the body, scrape the tailgate area, lower flaps, and leave the tarp in the open position, then drives away to return to the plant to return for another load.
13. After the last delivery, the truck driver will return to his depot.

The usual rules for all operations applied such as only one truck at a time could be sampled, lubricated, or off-load. With a single-bin operation at this mobile plant, only one truck may receive their load, also.

2.3 Develop the Simulation Model and Animation

The simulation model was constructed using the latest professional version of GPSS/H for the simulation and PROOF PROFESSIONAL ®. The simulation model uses data files for the travel times for each segment of the truck cycle. These consist of over 50 such paths. As each truck starts on a segment, a test is made to see what type of truck it is. Since there are 3 types of trucks used in the system, a sample is made from one of three different travel time functions. These functions can easily be changed as more data is obtained.

The program is interactive whereby the user is asked to input the numbers for each type of truck, the target loads for the day and other relevant parameters that might change as the construction progresses. The output from the program is placed into a data files for further manipulation via a spread sheet by the user.

The main simulation program was written in a general form so that it could easily be changed as the logic of the system might change over time. It uses data files for all segments of the program which can each be
changed as the system will change over time. Many of these changes can be made by company personnel with little knowledge of the software. Refer below to a bird’s-eye view of a progression of the study and an animated simulation model:

![Image 1](animation_screenshot.png)

**Image 1:** Animation screenshot of a discrete simulation study of an asphalt roadworks project.

### 2.3 Findings

#### 2.3.1 Stage I: Findings

Early stages of this project have revealed that team members may make different assumptions about work flow rates and provide a different opinion regarding sequential tasks – a site supervisor may report different probable work flow production outputs than that reported by the project manager, for example. Already, the process of engaging detailed work flow analysis with validation has facilitated project communication. The interviews about discrete events have challenged management to reconsider task efficiencies. For example, a supervisor questioned whether tip truck drivers needed to stop, exit their cab, and climb a stand to spray emulsion in the body of the truck before every load pick up. This is one assumed task that may have remained unchallenged without this review. Discussion has begun about human interface and risk-exposure throughout the system. This participatory analysis is engaging project teams to evaluate efficiency and safety. It is promoting effective communication to achieve optimum clarity about project operations. This practice may expand and enhance opportunities for human-centred design of work systems, complex risk assessment, communication, productivity management, and learning and development.

#### 2.3.2 Stage II: Plans

Now that the simulation model is developing the project management teams are asking questions relevant to production management. For example:

- *What might be a suitable number of trucks, and truck size, in order to achieve the most efficient cartage of 1500 tonne per day, on average?*
• What does the system look like if plant tonnage per hour increases (or decreases)? What are the net effects to work hours and truck times on site?
• If production time varies from start up to shut down, what is the impact to the system?
• Do budget costs vary if a change is made elsewhere in the system – number of rounds, tonnes per round, waiting times, or production activity?
• What might occur with a “black swan” event when likely events go awry? What is our level of preparation for these risks?
• Can the model be used for forecasting and tender response?

Another question of interest to learning and development, quality assurance, and management teams is:

• May I use this animation to educate team members on the project, new recruits, administration teams, advisory teams, or those engaged in civil construction training?

The following activities are planned for Stage II of this project:

1. Sit-down meetings to play the animation and review the simulation design assumptions, or test new possible occurrences – this will involve remote communications with the simulation designer
2. Training to project managers to use the software to input event changes dynamically, as they occur
3. Realisation of project goal validity or need for design changes
4. Evaluation of system performance or controls, and re-evaluation as needed.
5. Ongoing on-site visits and video of live performance of work flow – truck delivery, plant operations, and loading or off-loading procedures
6. Ergonomic review, implementation of global and specific design ideals, and ongoing modifications or revisions with re-evaluation
7. Ongoing evaluation of the merits - strengths, weaknesses, opportunities and threats - of employing simulation and ergonomic review of organisational systems

3. Implications for Industry

This ongoing work has shown that employing discrete simulation and animation in a roadworks construction project offers a strong communication tool to challenge assumptions, assure alignment in operational team situation awareness, provide support to learning and development, and contribute to resilience engineering where productivity and event forecasting may become routine part of business practice. It is a tool that may support the development of organisational ergonomics programs in which a framework is provided to operations management to analyse work organisation and design.

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References


