MISG 2003

Equation Free Summaries

Centre for Industrial and Applied Mathematics

University of South Australia

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Introduction

The Mathematics in Industry Study Group, MISG 2003, was held at the City East Campus of the University of South Australia from 3 to 7 February. The Study Group is an annual problem-solving workshop where industrial mathematicians from universities, government, and industry work on specific industry projects. It is a Special Interest Group of Australian and New Zealand Applied Mathematics (ANZIAM), a division of the Australian Mathematical Society.

This year six projects were presented, and about 110 delegates attended. Professor Phil Howlett was the Study Group Director and Doctors Yvonne Stokes and Stephen Lucas the Project Coordinators. The projects are as listed in the table of contents on the previous page.

At MISG 2003 we continued to emphasise the important role of both undergraduate and postgraduate students as the industrial mathematicians of the future and as the future representatives of industry. Students, assisted by designated mentors, were active participants in problem solving activities. At a plenary session, Giles Richardson of the University of Nottingham discussed two study group problems from his experience.

These equation free summaries have been produced by Tim Thwaites, a Melbourne based science journalist who attended MISG 2003, in conjunction with the project managers and the industry representatives. Each summary briefly describes the work carried out during MISG and gives recommendations about the outcomes. Full technical reports will be available in the proceedings that will appear in due course.

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SUBMARINE LEAD ACID BATTERY PERFORMANCE MODEL

Australian Submarine Corporation

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Australian Submarine Corporation (ASC) is the builder of Australia's new fleet of Collins Class submarines. Since completing construction of the new vessels the company has re-focused to become a service organisation dedicated to ensuring that the Royal Australian Navy continues to have access to six fully operational submarines. This includes arranging through-life support and ongoing access to key technologies. The company now employs about 900 people in two facilities—at Outer Harbor in Adelaide and at HMAS Stirling on Garden Island south of Perth, where the fleet is stationed.

The Collins Class submarines are the largest non-nuclear submarines currently in service. They are about 80 metres long, displace about 3000 tonnes, and carry a crew of six officers and 36 sailors.

When the submarines are fully submerged, the only source of power comes from banks of flooded lead acid batteries housed in four compartments. The submarines must eventually come to the surface to recharge these batteries using electric generators powered by three V-18 diesel engines. They can do so rapidly and without breaking the surface if necessary, using a snorkel to draw in oxygen in a process known as snorting.

Typically, submarine batteries are subjected to a cyclic regime that is very different from that of a working car battery. The batteries are repeatedly discharged and recharged, but each discharge is partial, and throughout the cycle the batteries are never fully recharged. This procedure is continued until the batteries reach a point where discharge takes them to levels below about half their maximum possible charge. At this point they are deemed to need a longer recharge to bring them close to full charge again.

The ASC is developing a computer model detailing energy flows aboard the Collins Class submarines. This submarine performance model will be used to assess the impact of design changes, provide advice on the operation of the submarines, assist with research into their performance, and help with maintenance.

Fundamental to the overall performance of the submarine is the performance of the batteries. It determines the proportion of time spent recharging (the lower, the better), and how far the submarine can travel underwater, and it also impacts on the overall range of the vessel. So a sub-model of the energy flows in the batteries is an important part of the overall submarine performance model.

The ASC asked the MISG to determine what techniques would be best suited to representing the battery systems, what measurable battery characteristics would be required to define such a model, and what would be the best design for the model.

Members of the MISG team came up with a wide range of approaches to constructing the model of battery performance—from a model that drew upon the details of the electrochemical reactions, to others that looked at the relationships between voltage and current, and one that simply fitted standard mathematical equations to experimental data. Good progress was made towards solving these models, but more data is needed to assess how well they will work in practice.

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The ASC provided several specifications for the battery model. The company asked, for instance, that the model should manage energy into and out of the battery, calculate available capacity, be able to determine cell voltage, calculate cell temperature (which affects performance), and account for loss of capacity due to operational profile and age.

The submarines use two distinct profiles for charging and discharging their batteries—a transit profile and a patrol profile. The transit profile is used when moving to and from a patrol area at cruising speed. During this time, the cycle of charge and discharge occurs at about three times the rate that it does in the patrol profile. While on patrol, the submarine is moving at slow speed and minimising its visits to the surface.

At no time after it is initially charged does the battery reach full charge again, because it would take too long to do so. In addition, lead sulphate begins to build up on the terminals, blocking molecular access and interfering with the chemical reactions occurring there. Also, as the battery ages the terminals begin to corrode. In fact, the energy available at any time is dependent on the previous discharge history, and the relationship between the energy input and resultant charge is not linear. Charge capacity varies with the battery temperature, and generally decreases with age and the number of charge-discharge cycles the battery has been through.

The ASC wants the model to be able to predict certain characteristics of a battery—such as its likely capacity at different discharge rates and its maximum charge current—from data measured at its initial charge. When the battery is in operation, the model must enable the calculation of charge at the end of a discharge-charge cycle, which means it must incorporate something of the battery's charging history.

The MISG team came up with four alternative models. The most detailed tracked the electrochemical reactions occurring in the battery acid and described the movement of charge by diffusion and convection between the terminals of the battery. Assuming that overall charge balances within the battery, a system of equations can be generated which, when solved, can give the rate of accumulation of charge on the terminals. Although the model has been completed, it will be necessary to apply standard numerical solution procedures to the equations in order to confirm that the model provides sensible results. To make the model more realistic and useful, a term that corrects for the build-up of lead sulphate on the battery terminals needs to be added.

A second model was constructed from a set of differential equations for changes in the concentrations of the ions involved in the reactions occurring at the positive and negative terminals. Using this model, estimates of the changes in voltage over time when drawing a constant current seemed to give sensible answers when graphed. Once again, there is a need to test this model with real data.

The third approach steered clear of chemistry altogether. It modelled the charge and discharge of the battery as if it were two connected compartments of water—a smaller compartment to model the electrode and a larger one to model the battery reserve. Drawing water from the first compartment, for instance, lowers the water level in the reserve compartment to replace what has been taken. In much the same way, drawing charge from the electrode lowers the reserve charge in the battery. The charging process would push things the other way. Once the model is adjusted to fit real battery data, it can then be used to predict future voltages and current.

The final approach was simply to derive an experimental model by generating empirical equations to fit the relationships between the various characteristics of the battery, such as voltage and current, over time. The US Department of Energy has produced a model of this type that could be used as a basis for the work of the team. A term to incorporate past history can be included.

So the MISG team came up with a wide spectrum of models, and made good progress in solving them. The next stage will be to test and validate them with more data—in particular to see if they can forecast battery capacity given past history.

"It was a privilege to be at the genesis of a new model—to see how these guys go about it," said industry representative Mr Glenn Bate. The conference had provided an opportunity to look at the range of models available and ASC is looking forward to identifying which one best fits the company's purpose. "I enjoyed it all. It was a unique experience and environment," Mr Bate said.

THE EFFECTS OF DEADLOCK AVOIDANCE ON RAIL NETWORK CAPACITY AND PERFORMANCE

Cooperative Research Centre for Railway Engineering and Technologies

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The Cooperative Research Centre for Railway Engineering and Technologies (Rail CRC) was established in 2000 to develop innovative and competitive solutions to the challenges facing the rail industry. It is undertaking research projects in six different areas or themes, one of which (Theme 3) is entitled Optimal Traffic Control and Scheduling.

In the movement of general freight in Australia, rail dominates the market. It is increasing its share of the long haul market across the Nullarbor Plain to and from Perth where it is relatively cheap and reliable. But rail is losing out to road on the shorter haul Sydney-Melbourne market. Rail customers would all like to see greater predictability, so that trains arrive when they are expected, and they also demand lower transport costs.

Most of Australia's long-haul rail network comprises single-line track with occasional loops or sidings to allow trains to pass or overtake one another. Operating such a system efficiently demands careful scheduling to ensure that trains are not kept waiting at a loop for long periods of time.

At present, scheduling is done manually. Detailed train plans are developed and refined over weeks. The industry, however, would like to move to automated methods that can develop schedules in real- or near real-time. It is hoped that such tools will lead to lower costs, better use of the available capacity and an ability to pinpoint where new capacity is needed. Also, reducing crossing delays and building more robust schedules could improve the reliability of the system.

One classic issue of automatic train planning is the avoidance of deadlock, when trains are so positioned on the network that it becomes impossible to move any one of them forward to its destination. This becomes more likely as the number of trains using the network increases, or when trains begin to exceed the size of some of the crossing loops.

Nothing less than complete elimination of deadlock is a necessity for any scheduling process. This is relatively easy for skilled operators using manual scheduling, because they can "look ahead" and avoid local congestion. Automating this predictive ability, however, is difficult. So the Rail CRC asked the MISG whether mathematical tools could be developed to ensure deadlock is ruled out of any automated scheduling process, without having to introduce overly restrictive practices, such as outlawing overlong trains. The development of such deadlock avoidance theory and techniques could also lead to ways of evaluating network capacity and performance, the CRC thought.

The MISG team came up with at least two mathematical approaches to deadlock avoidance. One relied on coding the location of every train on the network and assessing all possible changes of this state. The other used the numbers of alternative pathways of each train to its destination as the means of assessment. Members of the team also explored train and track configurations and operational rules that would reduce the possibility of deadlock.

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At present, a detailed timetable for train movements on any one day, including crossing locations and times, is developed weeks in advance. These schedules are important not only to ensure a smoothly operating system, but also to provide customers with certainty of freight movement, and to allow the rail companies to incorporate train and track maintenance. As circumstances change, however, the original timetable is modified over time, up to the day of operation when it is presented to the train controller. He or she then has to make the plan work by revising it continually in response to unforeseen operational disturbances.

Such manual techniques cannot provide the robust and flexible schedules the industry needs to satisfy its market. So the Rail CRC is undertaking a project to develop automated tools that can calculate schedules in real- or near real- time. It is expected that these tools will lower the costs of transport because they should allow the available capacity to be better used, expose where money can be spent to upgrade the system with most impact, and result in more efficient schedules that release capacity for necessary maintenance. Reliability will also be improved because the schedules should be less susceptible to delay and able to be adjusted quickly when the unforeseen happens.

Such automated tools, however, need to include the capability to detect and discard any schedules leading to deadlock. In order that this be done most efficiently the impact of deadlock avoidance on network capacity needs to be understood, so that overly conservative solutions can be avoided. Hence, a more complete understanding of deadlock avoidance should allow “higher risk” schedules to be considered, especially in areas of high population, where freight trains are often held back to ensure fewer delays to passenger services.

In 1983, Peterson and Taylor modelled train movements and introduced rules to make sure that they do not lead to deadlock. But their method, though fast, assumes a simple rail network comprising a single track with loops, and that no train is longer than any loop on the system. The Peterson and Taylor method also disallows several useful movements that would not necessarily lead to deadlock. The MISG team set about devising a more general model.

First, the rail network is divided into segments, each of which is numbered. The state of the network can then be represented by a string of the numbers of the segments occupied by trains. A graph or state transition network can be produced for all these combinations or states and the paths or transitions leading into and out of them.

Since no segment can contain two trains, certain states are impossible. There are also certain states that are unreachable, and these can be deleted. Deadlocked states are those with no paths leading out of them. The graph also allows the identification of critical states where trains must pass each other.

It soon became obvious to the MISG team that such state transition networks rapidly become hugely complex, especially in areas where the rail network can provide trains with many alternative paths. Even when rules are made to reduce the numbers of possible states the rail network can assume, the state transition network is typically much too unwieldy to work with. The team reached the conclusion that such a model was only likely to be of use in examining local subsets of the deadlock problem.

Three members of the team investigated another method for resolving the deadlock problem, by using the number of pathways a train has available to it to move forward from a segment at any particular time. Subsequent to the MISG Workshop, these ideas have been developed to include the case where not all trains can use all loops.

One team member also looked at the possibility of modifications to the method of Peterson and Taylor to make it more useful in real network situations. Others explored track configurations, train configurations and rules of operation that would make deadlock less likely to occur.

Queensland Rail’s Paul Milevskiy represented the Rail CRC in bringing this project to the MISG. He was surprised by the depth of mathematical theory involved in systematic approaches to deadlock avoidance in automated train planning, and was pleased with the progress made.

ANALYSIS OF HIERARCHICAL GAMES

Defence Science and Technology Organisation

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The Defence Science and Technology Organisation (DSTO) provides R&D and advisory support to the Australian Defence Forces, and is also interested in the transfer and application to civilian industry of technologies originally developed for the military. Of about 3000 scientists and support personnel in the DSTO, about 1800 work at Edinburgh in South Australia, 200 of whom are in the Land Operations Division which is an interdisciplinary group responsible for operations research, human factors and the exploration of future army systems.

One of the Division's major projects is to look at automated decision-making on the battlefield at the command or strategic level. In the past this has involved experiments running huge computer simulations of battle scenarios. The sheer size and complexity of these operations mean that only one or two runs can be attempted to investigate any particular scenario, providing extremely limited scope for statistical analysis. Hence, more recently there has been a move towards studying the smaller, simpler elements of which a battle is composed. Repeated simulation of these simpler models can lead to a good statistical understanding of the fundamental principles, and this insight can then be used to develop integrated models of more complex situations.

Games such as tennis, go and chess have much in common with military conflict. In particular, tennis is a series of repeated conflicts that provides a useful analogue to a typical battlefield situation. The hierarchical scoring—with points combining to form games, games building into sets, and sets into matches—reflects a military campaign.

A typical battlefield scenario, such as a simple raid on the enemy, can be modelled in tennis by a single point. How much force should the commander employ? How much effort should the tennis player expend? Should a commander use all available resources in an attempt to weaken an enemy who may respond with a strategic retreat, or should a good general keep some forces in reserve, and run the risk of the attack being overwhelmed? A tennis player must ask similar questions.

DSTO asked the MISG to investigate a framework for modelling an iterated, hierarchical game such as tennis. In particular the organisation wanted to know the extent to which tennis could be used as an analogue for land battle; the way in which the hierarchical nature of the scoring influences the result of the match; and the impact on the game of intangibles such as morale.

The MISG team formulated a set of relationships to determine how winning (or losing) individual points in tennis affects the probability of winning the match. Not all points have an equal impact on the probability of winning, so the optimum effort to expend in winning any one point may vary. To reflect this, the team defined a measure of the importance of a point—how critical it is to the outcome—and also introduced the concept of a strategic boost, in which extra effort is expended to win a critical point. The group also explored how to insert the idea of momentum or morale into the model.

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The game of tennis—where the process of playing points under the same basic rules is repeated over and over, and where scoring is hierarchical, with points building into games, sets and matches—provides a useful analogue for several other human endeavours, including diplomacy and economics, as well as military campaigns. The parallels with military activity can be close. In both cases, participants have limited supplies of energy (resources) and power. Such resources must be used strategically if one wishes to maximise performance.

Perhaps the most significant similarity between a tennis match and a military campaign is that the participant who wins the most points does not necessarily win the match, and the army that wins the most battles does not necessarily win the war. Not all points or battles are of equal value to each participant. So how hard should each player try for a particular point, given that he or she must expend a certain amount of energy to win the point, and that energy is a finite resource?

Several mathematical analyses of tennis are already available in the literature, but none so far seems to have come to grips with the shifting nature of the game. Game Theory analysis, for instance, takes a purely statistical view and tends to assume that all points are of equal importance. A somewhat more sophisticated model has been developed where server and receiver can decide to give up certain points quickly, and fight out others, but it presupposes a set strategy on the part of an opponent. Clearly, in real life, both players can change their strategy during the course of a match.

DSTO wanted to gain insight into such questions as how the importance of points varies for each player according to the score, and whether he or she is serving or receiving. If extra energy is expended to win a point, will this help the player to win the match? How possible is it to generalise from tennis with its set rules and discrete play events to more complex activities? Can psychological effects, such as morale, be incorporated into the analysis?

The MISG team began by formulating a set of mathematical terms and relationships describing the probability of winning any one point, whether serving or receiving, and also of winning a game, set or match given a particular score. In the course of setting up this mathematical description of the problem, the team defined a unit of extra effort, “the boost”, that each player could expend on particular, nominated points. But boosts were held to be a finite resource, limited in number. Many of the questions to be answered in the end depend on knowing where and when to boost. The strategy of boosting clearly has to involve some understanding of the importance of an individual point to the outcome of the match. Hence the team also defined a measure of the “importance” of points.

The team used its basic terms and relationships to express logical propositions in mathematical ways. One such proposition, for instance, was that the importance of particular points is only established once a game has begun—importance does not matter if you have not started a game. When the team’s formulations were extended to multiple games, certain logical outcomes emerged as to where in general to apply boosts—when you are behind on serve, for instance, and when you are receiving and ahead in a game.

The MISG team put together some strategies or algorithms for playing a match. It came to the conclusion that if points were ranked in terms of importance in a match, and a set number of boosts were allowed, it was possible to estimate a level of importance above which one should always boost. That level depends on how much energy the player has in store with which to boost.

The team also concluded that a real game of tennis would generally be concluded in fewer games than expected on the basis of its model. The difference relates to the psychological factor known as momentum, which includes such things as morale and confidence on the positive side, and giving up or choking on the negative. The impact of these could be added to the model.

Commenting on the team’s work, Dr George Galanis from DSTO said he was impressed with how well the team members had recognised the importance of the project beyond the game of tennis. The work had been of real practical benefit, he said, and may well impinge on the experimental program at the DSTO. Dr Galanis had been very impressed by the dedication of the individual members of the MISG team, their “sheer intelligence” and their keenness to pursue the problem. “That sort of enthusiasm rubs off,” he said.

PARTICLE TRANSPORT THROUGH THE FROTH LAYER IN COLUMN FLOTATION

Ian Wark Research Institute

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The Ian Wark Research Institute is an Australian Research Council Special Research Centre at the University of South Australia. It conducts fundamental and applied research into minerals and materials, and is named after a pioneering Australian minerals scientist. Founded in 1994, it now has a staff of about 140 and an annual budget of $9.5 million.

One of the Institute's current research projects is to model and investigate the process of flotation that is used widely in mineral processing to separate mineral particles from the rock in which they occur. Broadly speaking, particles of crushed ore are suspended in a mixture of water and reagents, known as pulp, in a flotation cell. Air is bubbled from the bottom of the cell through the pulp, creating a froth or foam on top. The valuable mineral particles become coated with reagents to make them attractive to air, and attach themselves to the rising bubbles which transport them into the foam where they can be concentrated and skimmed off. The gangue, or non-valuable particles, remain in the cell and are discarded.

In detail, however, the process is much more complex, with liquid containing both types of particles moving into the foam and fluid draining back into the pulp. At present, the Institute has useful models for what goes on in the pulp in terms of the capture and transport of particles, but there are no corresponding models for particle transport and fluid flow in the froth. The Institute asked the MISG for advice on how to generate these models, with the objective of being able to describe the whole flotation process.

The MISG team took two broad approaches. First, it brought together and analysed what it could find in the literature relating to the problem, and particularly to fluid flow in the froth layer. From these considerations, the team was able to draw several conclusions as to what needed to be done. Second, the team began to formulate its own equations to describe what happens in the froth.

The team concluded that the existing equations describing fluid drainage in foam describe extreme cases and can be made more generally applicable. It also decided that the action of surfactants in stabilising foams needs more attention, and that drainage becomes almost irrelevant to particles in foams that are moving up to overflow the column. In fact, the team determined that particles caught up in the foam have little chance of returning to the pulp.

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Foams or froths are composed of gas bubbles enclosed by liquids, and sometimes solids. They are important commercially not only in mineral processing, but also in beer, ice cream, soaps and polyurethane. Any work on froth systems potentially has wide applicability. The foam bubbles are connected by thin films or lamellae, and are usually stabilised by a surfactant. Where three or more bubbles meet, tubes of roughly triangular cross-section form. These tubes are known as Plateau borders, and comprise a network in the froth through which liquid flows.

The questions on which the team worked seemed simple. What does the fluid do in the froth layer? What happens to the bubbles? How do particles affect fluid flow? In contrast to this apparent simplicity, the activity occurring in the foam is highly complex. It includes entrainment of liquid and particles from the pulp zone into the froth; simultaneous upward and downward movement of liquid in the froth; changes in the shape of bubbles and lamellae as they rise; coalescence of bubbles; the release of gas from bursting bubbles at the top; and much more.

In the literature, the MISG team found several equations for fluid drainage in foams. Fluid moves through the Plateau borders in a manner described by Poiseuille in the mid-19th century for the motion of liquids in tubes of small diameter. The dominant forces are capillary and gravitational. When the team looked at experimental evidence, it found that both the Poiseuille relationship and a refinement that includes other forces such as viscosity describe extreme versions of a more general case. Another model from the literature took into account bubble breakage and replenishment, and the team recognised this could be adapted further to describe the kinds of froths used in mineral processing.

The mineral particles themselves need to be taken into account in any exploration of the flotation process. The MISG team determined that the hydrophobic particles, those that stick to the bubbles, affect the froth in different ways according to the relative particle size. Particles that are small with respect to the width of the bubble lamellae can support these films, and will certainly change the properties of the surfactants that stabilise the foams. Medium-sized particles which can span thin films may rupture them, and large particles may not be supported at all and could detach and cause the froth to collapse. With hydrophilic particles, generally only the smaller particles will flow up into the foam, but once there, so long as there is a net upward flow of fluid, are unlikely to drain back into the pulp. This means that it may be possible to measure the efficiency of the froth in trapping particles by means of a simple flow rate, rather than having to construct a detailed and complicated model.

Members of the team also began to formulate equations that describe what happens in the froth, based on natural conservation laws and on experimental observation. Contrary to conclusions that appear in the literature, for instance, they noticed that in column flotation, the bubbles become larger as they move to the top of the column, their borders become smaller, and they move less relative to one another. Moreover, because of pressure, they are never spherical, but always slightly flatter on the bottom.

The equations that the team developed describe the system in terms of measures of state such as overall volume, water and air content, and surface area of bubbles. The team introduced a measure of average thickness for Plateau borders, because it allows a more accurate estimation of the water content of the foam. This measure is related to change in surface area in a way that is as yet unspecified.

With respect to particles, the team came to several conclusions, some of which were hotly debated by the industry representatives. Any hydrophilic particles that enter the froth, the team determined, have little chance of returning to the pulp. Hydrophobic particles will continue to travel with the surface of the bubbles unless the surface area decreases and they are crowded out by other particles. The likelihood of returning to the pulp is greater for large hydrophobic particles.

Industry representative George Tsatouhas said he was impressed with the energy and enthusiasm of the group. “We presented the MISG with a very complex problem. It was an excellent exercise to generate a fresh approach. We were able to look at the building blocks and details of the drainage equations. I was delighted to participate. Thanks for the whole week.”

PREDICTION OF HEAT LOSS AND ENERGY REQUIREMENTS IN STEEL MAKING VESSELS

New Zealand Steel

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New Zealand Steel is a world leader in manufacturing steel from iron sands. At its mill in South Auckland, New Zealand's only integrated steel maker produces about 600,000 tonnes of steel a year as coil, plate and pipe.

Initially, molten iron is produced by reducing iron sands using coal and heating the product in electrically powered melters. The iron is then purified and turned into steel. In the key process, known as Kombiniert Oxygen Bottom-blowing Maxhutte (KOBM), molten iron, scrap steel and fuel additives are combined in a vessel through which oxygen is blown.

The KOBM process, which was developed in Austria, takes place in a squat, barrel-shaped vessel that can be rotated through 360°. The vessels at New Zealand Steel are about 5.6 m in diameter and 6 m high, and produce batches of about 74 tonnes of steel in around 40 minutes. A new KOBM vessel is a steel shell lined with 150 tonnes of refractory bricks to a thickness of about 75 cm. This lining wears down to about 5 cm after the vessel has been used for about five or six weeks to produce about 1000 batches of steel. At this point the vessel is taken out of service for relining.

Generally, steel is produced in sequences of between eight and 12 batches in a row with a 5 to 10 minute break between each batch or heat. The time between sequences is used for cleaning and maintenance and can vary from 45 minutes to 10 hours. Because the vessel cools down between heats and sequences, considerable energy must be expended at the beginning of the next heat or sequence to bring the vessel back up to the temperature necessary for adequate completion of the steel making process. In order to ensure this end-point has been reached, the temperature of the molten steel inside the vessel is measured at the end of each heat.

New Zealand Steel asked the MISG if it could improve prediction of the endpoint of the steel making process by estimating how much energy is lost from the KOBM vessel during each heat. The solution very much depends on what happens between each heat and each sequence, and also on the thickness of the refractory lining, which varies throughout the vessel's lifetime. But it would enable NZ Steel to predict more precisely the energy deficit for the next heating round.

After considering the mass and energy flows in the vessel, and assembling and reviewing the available thermodynamic data, the team focused its attention on the time between successive heats. It approached the problem by generating a hierarchy of increasingly complex and sophisticated models, each providing useful information to help with constructing the next, and each of which could answer, to some degree of approximation, the key question.

Although not all the models were completed, the team reached some important conclusions—that when a new vessel is used it takes up to three days or 80 heats to heat up the refractory lining to a steady state, that radiation dominates convection as a source of heat loss, and that the main changes in temperature occur around the bottom surface of the vessel. The process demonstrated the need for more data on how the lining wears over time and according to its position in the vessel.

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The industry representatives provided a broad overview of the energy relationships of the KOBM process. During the heat, the energy of the molten iron put into the vessel together with the energy generated from the chemical reactions between the impurities in the iron and the oxygen blown into the vessel has to equal the energy of the steel and slag. Several other factors to do with the gases emitted and the state of the lining, and the heat lost from the vessel also have to be taken into account. The problem put to the MISG team was to find a simple method to calculate these additional terms.

In fact, the task amounted to predicting how much fuel needs to be added to any particular heat to achieve a target temperature of about 1720ºC for making steel. The estimate varies according to what has happened to the vessel in the past. It depends, for instance, on the length of time taken between heats, what cleaning and maintenance activities have taken place between sequences, and when the steel has been tapped and how long it took to do so. It is also necessary to know how much the refractory lining has worn, and whether the vessel needs to be reheated to complete the steel-making process.

The team concentrated its attention on the cooling of the vessel between tapping the steel from one heat and charging the vessel for the next. It started by assembling measures for some significant thermodynamic properties associated with the process, such as how quickly heat diffuses through the refractory brick. This together with the thickness of the lining provided an estimate of how long the lining takes to heat when the vessel first comes into service. The answer is about 80 heats or three days.

An analysis of the heat transfer processes showed the importance of the surfaces of the vessel wall surface, because radiation of heat dominates convection. Heat loss via radiation from the outside of the vessel is about 10 times that lost by convection. Inside the vessel the disparity is even more pronounced—heat loss by radiation from the refractory lining is about 100 times that by convection.

The team ended up splitting into groups to produce five models of heat loss during the period between heats. The first was a purely statistical model. It used the available data on temperatures achieved in each melt and the time between heats, together with information on the ingredients in the melt to generate an empirical relationship. When the model was employed to predict temperatures, it performed consistently and well. Such a model provides little in the way of insight, however, except that expected from extrapolation—and it would not cope with new patterns of operation.

The other four models were based on principles of heat transfer, and formed a hierarchy of increasing sophistication and complexity. The first simply looked at the heat balance in the vessel, treating it as a single unit. It considered general measures such as the temperature of the exit gas from the vessel and the average temperature of the refractory lining in terms of radiation, convection and conduction inside and outside the vessel. This analysis could be used to generate an equation to predict energy requirements for the next heat.

The second of the models took the analysis further, replacing the average temperature of the refractory bricks with equations that acknowledged the change in temperature through the vessel wall from less that 40ºC outside to more than 1350ºC inside. It could provide a measure of the heat deficit below the target temperature, and hence the amount of fuel that needs to be added. Although the model was not quite complete at the end of the MISG Workshop, a pathway to a simpler model was becoming evident. The temperatures were expressed in terms of radiation and convection. But the dominance of radiation in heat loss is so apparent that the convection term may become irrelevant.

The third model of the hierarchy is a two dimensional simulation which acknowledges the fact that different areas of the vessel contribute differently to heat loss. Enough was completed of this model to show that the main changes in temperature occur around the bottom surfaces of the vessel.

The fourth model implemented was a full three-dimensional model using the (CSIRO-developed) software package FASTFLO. It produced good visual output for the resulting thermal regimes, but could not, without substantial additional work, cope with the non-linear boundary conditions.

It was the first time New Zealand Steel had been involved in such an exercise, industry representative Neil McGillivray said, and it had been an interesting experience. “There are still a few steps to go before the work can be put to use,” he said, “but I enjoyed the week, and it provided me with a much better understanding of what is happening.” He then thanked all who had worked on the project. Follow-up work is proceeding in Auckland.

BEST UTILISATION OF ROLLINGSTOCK ASSETS TO REDUCE COSTS WHILE MEETING CUSTOMER DEMAND

Queensland Rail

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Queensland Rail (QR) operates on one of the world's largest rail networks encompassing about 10,000 kilometres of track. It has a turnover of about $2 billion a year and about $7 billion worth of assets—locomotives, rollingstock, depots, stations, offices and the like.

QR's heavy haul coal business operates 24 hours a day, seven days a week, along five rail corridors, transporting about 135 million tonnes of coal a year from 32 mines to 11 unload terminals including ports and power stations. Each train runs a cycle from its depot to a mine where it is loaded with coal, then to an unload terminal where the train is emptied of its payload, and finally returns to the depot where it is prepared for the next trip. The rollingstock to support this business—diesel or electric locomotives and bottom-dumping wagons of different capacities—constitutes a significant capital cost and must be used efficiently.

QR asked the MISG to investigate how the available rollingstock could best be allocated among four of the corridors to provide trains to satisfy customer demand at the lowest cost given a subset of the many constraints of the existing system. The company also requested suggestions as to where investment in infrastructure would be justified to eliminate constraints.

Typical of these constraints is the length and number of passing loops. This restricts the length and number of trains able to use a corridor without congestion. The grades encountered restrict the tonnage any configuration of locomotives can haul, and track type determines the maximum capacity of wagon that can be used.

A preliminary analysis of the problem was undertaken to obtain an indication of how circumstances changed when the number of locomotives per train is varied. The group then worked at developing a model using integer programming techniques to provide a discrete set of solutions to the problem of allocating rollingstock to corridors.

The model allocated specific configurations of locomotives and wagons, known as consists, to each corridor. Each consist can have up to six locomotives, together with sets of wagons usually all of the same type. QR provided 'simulated' operating costs for the designated consists. The MISG model was based on minimising these costs.

Using the model, the MISG team compared the existing QR allocation with the MISG allocation. Based on the simulated operating costs used by the MISG study group, and if surplus rollingstock could be utilised in other QR businesses, the MISG distribution had the potential to save the company millions of dollars.

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The size and number of the trains working a corridor affects its operation and associated costs in many different ways. If the same rollingstock were split between many small trains, as opposed to a few larger trains, there would be increased crewing costs because more crews would be needed, and increased network congestion and transit times because more trains would be passing each other and queuing for terminals. On the other hand, smaller trains take less time to load and unload, so rollingstock utilisation is improved. Any allocation needs to take this into account.

Other constraints include such things as diesel and electric locomotives cannot be used together on the same train, some tracks are not electrified, and the largest wagon types must operate in pairs. QR prefers trains on a corridor to be of similar payload and to be able to service all mines and unload terminals. In addition, each corridor needs to be allocated extra rollingstock for contingencies such as maintenance or breakdown.

At present QR tackles the problem of rollingstock allocation by determining optimal train configurations based on corridor constraints and best utilisation of locomotives. This generally turns out to be the most cost effective option as well. Usually, a predominant configuration emerges as the lowest cost option for each corridor. Allocations are then made on this basis starting with one corridor and proceeding to the others. Alternative allocations can be made by selecting a different corridor as the starting point. After some reasonable alternatives have been considered, the final selection is a matter of judgement.

The MISG team began by conducting a literature search and by gathering information on the characteristics of the rollingstock and the corridors. Members of the team then generated some simple equations linking cycle times, the amount of coal to be carried in a corridor per year, the amount carried per train, and the number of trains necessary to satisfy demand.

QR uses a cost model that calculates the cost per tonne of coal transported from a mine to an unload terminal in a given corridor by a given train configuration. Built into this model are components for crewing, track access charges, rollingstock operation, and many other operational costs. For business reasons, QR was not able to provide the team with actual costs or cost components for a particular haul and train configuration from this model. However, ‘simulated’ costs for a reduced set of configurations per corridor were provided by the company. These configurations made optimal use of the available locomotive power.

In the end, the MISG team used a set of about 26 costed train configurations as input to its model, which then determined the number of each of these configurations to be allocated to each corridor. The MISG model solution allocated a slightly different mix of configurations to the corridors than is currently used by QR. Based on the simulated operating costs used by the MISG study group, and if surplus rollingstock could be utilised in other QR businesses, the MISG distribution had the potential to save the company millions of dollars. Time did not allow the MISG team to provide any suggestions on where investment in infrastructure would be justified to eliminate constraints.

The team was able to generate about 1500 other configurations that could be used to haul coal, but it was impractical to try them all in its model within the given time frame. It is also possible to make the MISG model more detailed and sophisticated, and to add further constraints.

QR representative Ms Caroline Camilleri said QR was pleased with the progress that had been made. The MISG team had been a pleasure to work with, she said, and remarkably patient about the constraints under which it had to labour. She would like to develop a more sophisticated model that includes “what if” capability for issues such as extending passing loops, purchasing additional rollingstock, or coping with increased tonnages from mines.

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