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System Dynamics Modelling of Occupational Safety: A Case Study Approach

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ABSTRACT

Occupational safety is a complex phenomenon. If occupational safety management is to be successful, not only the systematic but also the systemic aspects of safety need to be understood. System dynamics modelling appears to be an appropriate methodology for exploring the array of occupational safety strategies open to employers. Many system dynamics models of industrial systems have been built entirely for specific host firms. This paper illustrates an alternative approach. The process of developing a generic system dynamics model of occupational safety and testing it in an industrial setting is outlined. Particular emphasis is placed on building confidence in the model through the use of a rigorous set of structural, behavioural and policy tests. The findings of discussions with senior managers and other workforce employees are summarised. This discourse demonstrated that the model had both empirical validity and pedagogic utility. The outcome of this study is a robust system dynamics model. This model should have the capacity to be parameterised for any workplace in order to aid learning and policy making in the domain of occupational safety.

BACKGROUND TO THE OCCUPATIONAL SAFETY STUDY

Contemporary United Kingdom (UK) health and safety legislation encourages more self-regulation and active management of health and safety at work. Employers are responsible for managing the risks in the workplace that they create, rather than simply seeking to comply with specific health and safety regulations. In particular they are required to develop and document their occupational safety management systems. The onus now is on the employer to take practicable action to secure safe and healthy workplaces, along with maintenance of the systems to ensure their continuation.

The legal, moral and financial benefits of maintaining thorough safety management systems are becoming evident to employers. Despite improvements in occupational health and safety in recent years, there are still unacceptably high incidences of occupational accidents and ill-health. As well as the physical and mental costs to individuals and their families, the costs to business of the average accident are now estimated to be as high as £3,500 (Davies, 1998). Waring (1996) suggests that a major problem may lie with the content of many health and safety management publications. Often they are narrow and prescriptive and can give the impression that success can be delivered if a particular systematic ‘formula’ is acted upon. If health and safety management systems are to exploited to good effect, then both the systematic and systemic aspects of health and safety need to be understood. The use of models to explore and understand the consequences of decisions before action is taken may prove to be valuable where firms seek to evaluate alternative occupational safety strategies.

It appears that the established modelling methodologies may not be suitable for exploring occupational safety strategies as they neither capture the dynamic behaviour of the complex problem of accidents at work, nor identify the causal feedback structure contributing to that behaviour. This paper will describe the development of a dynamic simulation model of occupational safety strategy using system dynamics and its application in an industrial setting. Consideration is given to the future of the model as an aid for safety policy making and learning across a range of firms.

THE MODEL BUILDING PROCESS

The purpose of the study was first to build a generic occupational safety model (GOSM) to show how policies could be designed to both reduce accidents and also the financial costs of maintaining an effective SMS. Secondly, the GOSM would be translated a real world occupational safety model (RWOSM) and empirically tested. If these ambitions were successful achieved then this would offer scope for the GOSM to be re-parameterised and transferred between different employing organisations.

A rigorous model building process emerged which was transparent, iterative in nature, and emphasised a range of structural, behavioural and policy tests. This process is illustrated in Figure 1(validation tests are emphasised using italics, and where numbers are parenthesised this represents the re-application of a validation test). The model was developed in three distinctive phases: ‘conceptualisation’, ‘analysis’ and ‘evaluation’. Within these three broad phases, a number of activities were conducted. These activities were informed by mental, written and numerical data sources from beyond and within the host firm for the study. A fourth phase: ‘implementation’ has yet to be started.

MODEL CONCEPTUALISATION

The model conceptualisation phase consisted of defining a dynamic safety problem and identifying the causal structure likely to be contributing to the problem. When testing system dynamics models with real firms, the convention is to develop the study with the owners of the problem, or at least to consult them on a regular basis (see Lyneis, 1999; Homer, 1996, 1997 for examples). At the onset of the study there was no specific historical reference mode of behaviour to examine, nor was there a problem owner to consult. Consequently, if a reference mode of behaviour for the study could be set, and the causal structure thought to contribute towards its behaviour verified, this would require the investigation of a range of knowledge sources. Forrester (1980) identified three types data sources for system dynamics models: mental, written and numerical.

Knowledge Sources for Verifying Generic Occupational Safety Model

- The mental store of data encompassed: the personal assumptions of the modeller grounded in practical experience, and the insights and experiences of safety practitioners and academics.
- The written store of data was rich and varied and included: Health and Safety Executive (HSE) publications (guiding legal compliance and recommend good occupational safety practice); practitioner magazines (containing developments in safety practice), and

academic journals (outlining the findings of safety studies and proposing theoretical safety models and frameworks).

- Numerical safety data was available from many sources including: the Health and Safety Council (HSC) publications (annual UK occupational accident and illness statistics); the HSE (estimates of the costs to the UK economy of occupational accidents and illness); and practitioner and academic publications (safety opinion and practice survey results and findings of statistically based safety studies).

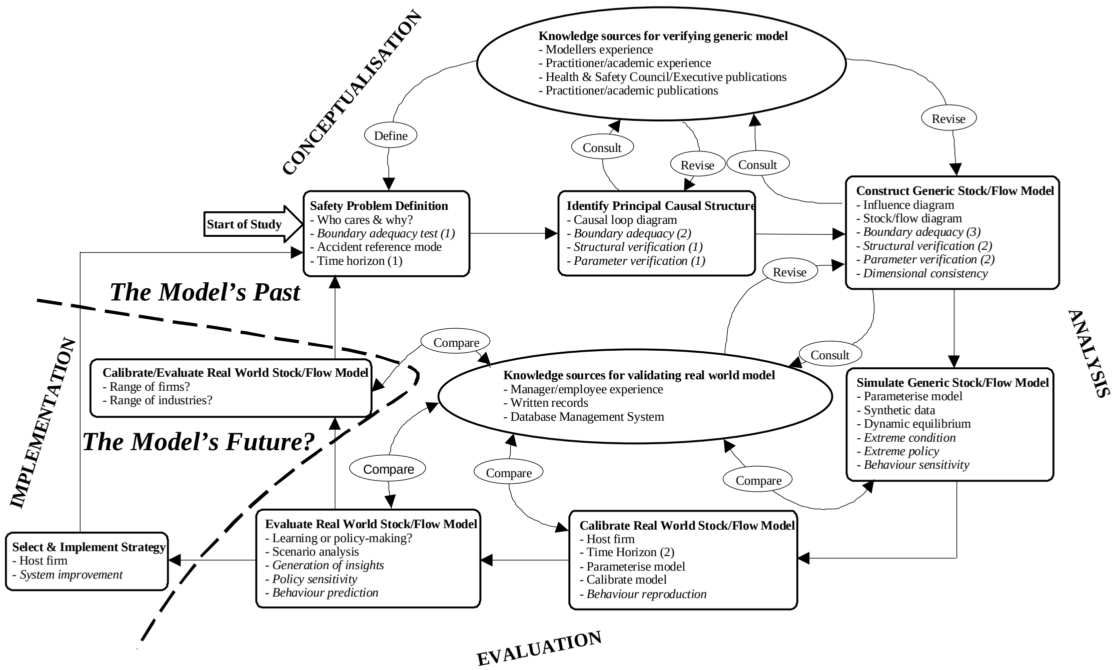

Figure 1 The Occupational Safety Modelling Process

Defining the Safety Problem

Many stakeholders (legislators, enforcers, trade unions, insurers, employers and employees) have an interest in the maintenance of robust occupational safety policies in employing organisations. It would appear though that employers and employees are the strongest stakeholders in occupational safety as they have the greatest control over accidents, and are affected most greatly by their consequences (morally, financially and legally). The boundary of the GOSM was limited to the single workplace in order to make it easier for the quantified system dynamics model to generate safety behaviour endogenously, and for the important policies and structure causing that behaviour to be more easily understood.

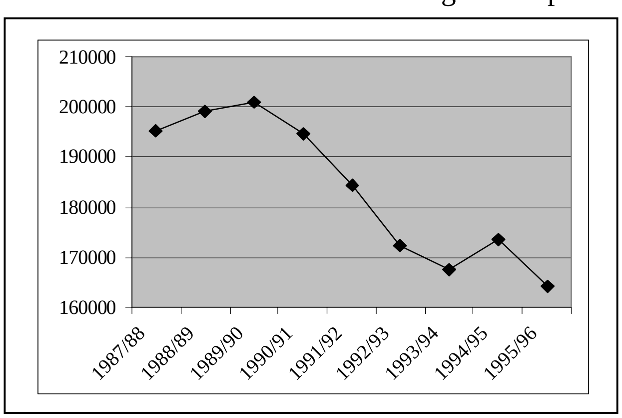

Figure 2 shows the dynamics of injury accidents nationally in the UK. This was set as the reference mode of behaviour. Occupational accidents are dynamic and problematic.

Figure 2 Total workplace injuries reported to the HSE 1987/88-1995/96 (HSC, 1998, p.17)

Accident patterns vary across different employing organisations, and an appropriate GOSM would need to be capable of reflecting this. It was decided that a time horizon of three years would be adequate for examining the dynamics of a SMS's behaviour. A shorter time frame could be unduly influenced by any short-term fluctuations; and evaluating safety performance over any longer period may have caused the model users to raise questions about the accuracy or suitability of the model's predictions.

Identify Principal Causal Structure

A causal loop diagram (CLD) was developed to explain the important causal linkages present in occupational SMS's. A CLD emerged which was thought to capture adequately the underlying structure of the accident problem confronting firms. The CLD is outlined in Figure 3.

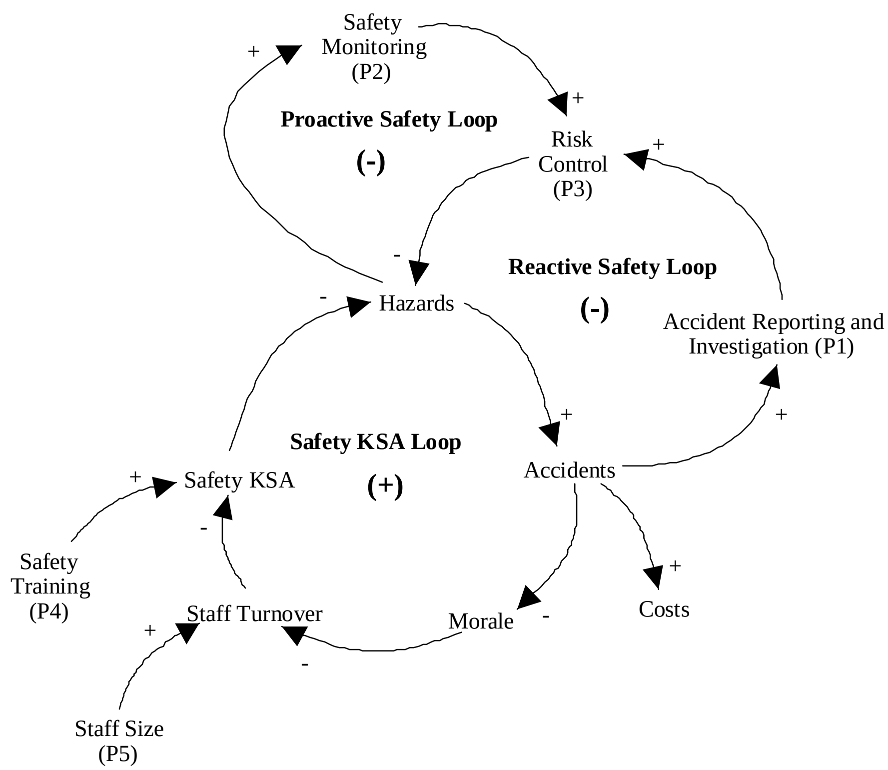

Figure 3 The basic causal feedback loop structure of the generic occupational safety model

Three feedback loops exist, one reinforcing and two balancing. A total of five potential policy areas are also identified as change parameters (P1-P5). Three of the five policies appear to be embedded within the feedback structure of the model. This is because the CLD was built with the intention of distilling and communicating ideas about the high-level model structure and feedback. All the policies can be regarded as aggregations of potential system parameters and variables. Each feedback loop was traced through to structurally verify its contents and to describe its operation. The CLD was compared against real world observations or published literature. As the causal feedback structure began to emerge, the adequacy of the model boundary had to be re-considered. A number of mental simulations were performed to help establish whether this aggregated causal loop structure would be likely to replicate the accident reference mode. The overall polarity of the CLD was negative. This suggested that relatively stable SMS's could be designed and implemented by employers to control accidents at work.

MODEL ANALYSIS

The model analysis phase consisted of representing the structure of a SMS in a system dynamics stock/flow model (SFM). This model purported to represent occupational safety structure and policy that was evident or at least desirable across a range of employing organisations. This model was labelled as the GOSM (see Moizer, 1999 for full description). The adequacy of its structure would only be established through analysing the behaviour generated by that generic structure.

Construct Generic Stock/Flow Diagram

The CLD was incrementally translated into a full SFM. A number of model sectors were identified and the stock/flow structure developed for each. These sectors were gradually linked together and further refinements to parts of the SFM ensued. Structural equations were assigned to all model variables.

A total of 51 parameters reside in the GOSM; of which 29 are constants, 16 are levels, and 6 are table functions. Thirty-one variables are also contained in the model, of which 19 are rates and 12 are auxiliaries. All the model components are endogenous to the system under study. Thirty-nine feedback loops are present in the GOSM. This is broken down into 13 reinforcing loops and 26 balancing loops. The dominance of balancing feedback loops (two-thirds: one-third) was in line with the CLD. This suggested that controlling the behaviour of the GOSM through policy parameter modification was possible.

Rigorous structural validation testing ensued. The structure of each equation and parameter was verified against both safety literature and the assumptions about relationships thought by experts to be present in real world occupational safety. Dimensional consistency tests were conducted on every model equation, not so much as to prove the equations dimensions were valid but rather to show that they were not mathematically incorrect. The structure of the model and its dimensions appeared to be consistent with those present or desirable in the SMS of a typical employer. The boundary of the GOSM guaranteed that the model structure was totally endogenous to the firm. This ensured that future policy implication tests allowed system behaviour to be generated by the policy decisions of the user, rather than emanating from an external source.

Simulate Generic Stock/Flow Model

A number of behavioural tests would be needed to further evaluate the validity of the model's structure. Synthetic data was used to parameterise the GOSM. Prior to any behavioural tests being performed, the GOSM was set to allow the 'base run' to simulate in a state of equilibrium. When conducting the behavioural tests, this would reduce the likelihood of an unanticipated shift in loop dominance, and also allow the exact effect of each parameter change to be measured clearly.

Extreme conditions and policy tests were used to determine whether the GOSM would behave reasonably when taken beyond its anticipated normal operating limits. These were achieved through modifying stocks or altering policy statements in an extreme way. The model did replicate the expected behaviour of a real occupational safety system faced with extreme conditions or policy circumstances (for example, where the labour force was set zero then there were zero accidents).

Parameter sensitivity tests could now be performed. These tests were concerned with identifying whether the GOSM was sensitive to certain parameter changes such as training, labour force size or accident risk; and whether the numerical and behavioural changes exhibited by the model would be acceptable in the system under study.

Three types of parameter were tested for sensitivity: constants, initial values of stocks, and table functions. It was important in the design of the sensitivity analysis to account for some of the major limitations associated with parameter sensitivity testing. The principal practical limitation would be the number of manual changes to the parameters' values that could be feasibly made, recorded and analysed. Only single parameter changes were made at a time. This allowed each parameter's effect to be more precisely assessed.

Coyle (1978) published the idea of producing a performance index (PI) to measure system dynamics models. He suggested that a PI could be useful when comparing one simulation run with another. A PI is usually a single number summarising the whole performance of a model run. This can allow easy presentation of conclusions and also gives a uniform comparison of one run with another. This approach was modified and used to examine the sensitivity of the model to given sets of parameter sensitivity tests (see Moizer, 1999 for full details). A range of measures of parameter sensitivity would surely build more confidence in the models plausibility. These measures of a number of key output metrics behaviour included:

- making parameter change and noting final values;
- measuring the settling time back to equilibrium following a parameter disturbance; and
- measuring the maximum value achieved following a parameter disturbance.

System dynamics models are insensitive to most parameter changes, but are sensitive to a few parameters in a model of a system. Given this rule, Spearman's Rank Correlation Coefficient was used to rank and measure the strength of association between the sets of parameter sensitivity results. Parameters were then categorised as being high, medium or low sensitivity. The results of these tests could help with translating the GOSM into an operational model in two ways. Firstly, the more sensitive parameters identified would be more accuracy set in the when empirically testing the RWOSM. Secondly, the policies most likely to offer the greatest leverage over safety performance in the host firm were now also established. This would aid the search for effective policy scenarios.

The most sensitive parameters found were associated with employment policies, those concerned with staff recruitment, retention and turnover; and the knowledge, skills and attitude of staff, rather than engineering control. This further added to plausibility of the model.

Model Evaluation

The model evaluation phase involved validating the model with real world data derived from a host firm, and examining whether the RWOSM could:

- replicate the past behaviour of important metrics of a real occupational SMS;
- aid managers in learning about the nature of safety management; and
- assist managers with safety policy making.

Knowledge Sources for Validating Real World Model

- The mental store of data encompasses the insights and practical experiences of managers, supervisory staff and line employees.
- The written store of data was largely contained on a database management system (DBMS), and included training, risk assessment, safety inspection and accident records. Full minutes and actions emanating from safety committee meetings and documented safety procedures were also useful seams of written safety material.
- Numerical safety data overlapped with much of the written material on the DBMS. This included accident and hazard statistics, length of service of employees and training programmes.

Calibrate Real World Stock/Flow Model

If an operational system dynamics model is to be accepted by the managers of a host firm as a policy analysis tool, they will often expect the model to replicate the past behaviour of the proposed system under study (Lyneis, 1999). The GOSM, being of an exploratory nature, could offer an insight into the problem of occupational safety, but without empirical detail and sufficient calibration it would be difficult to get the managers of a real firm to even think about making specific safety policy decisions based on these insights. The GOSM was converted from an exploratory model into an empirically based operational one. This was achieved by using safety data and experience derived from a host employer, and by developing a three-year historical representation of the key behaviour metrics of their SMS.

The first stage of developing the RWOSM involved the measurement and validation of all numerical parameter values in the model. The parameters were informed using hard data derived from the firm's DBMS and manual records; and more descriptive data obtained from discussions with managers and a survey of line employees. Many of the policies were found to be dynamic, and numerical time-series data would play a role in achieving a close historical match between model and reality.

The second stage concerned calibrating the RWOSM to replicate the past behaviour of the RWOSM. This was achieved by tuning the less measurable parameters and observing the closeness of fit between the actual and observed accident rate, and actual and observed distribution of hazards. These correspondences were measured using Theil's inequality statistic which identified whether the sources of error between observed and actual data and their composition were acceptable (see Sterman, 1984 for full guidance on method). Figure 4 compares the simulated and actual accidents.

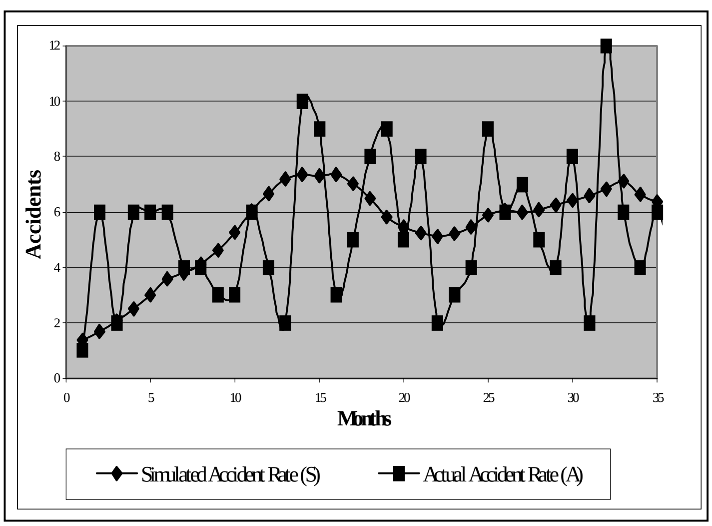

Figure 4 Simulated versus observed accident rate in the host firm over the previous three-year period

The purpose of validating the RWOSM and then replicating historical behaviour was not only to understand why the firm's SMS behaved in a certain way, but also to build the manager's confidence in the model as a plausible means of exploring future safety decisions. These possible future scenarios could be evaluated now with a greater level of confidence.

Evaluate Real World Stock/Flow Model

The RWOSM was built and subsequently validated with real data from a host firm with the intention of developing a means of improving insights into the real world problems of occupational safety. These insights could be brought about by learning about the effects of safety decisions, and/or through designing policies to improve safety system behaviour. The usefulness of the study would lie in showing the level of utility and effectiveness of the RWOSM as a policy-making and learning tool. A strong measure of its success would lie in whether the model was actually able to generate new insights or improve existing understanding about the nature of safety management in the firm.

Opinion on the model's uses as a policy making and/or learning tool was gathered through the use of an in-depth interview with a group of managers from within the host firm (see Moizer, 1997 for full description). Many of the explicit observations made by the group pointed to the model being more suitable as a tool for either demonstrating the effects of safety policy, or for helping people to learn more about their firm's safety management. There was acknowledgement that the simulation would still be of value in learning or even policy-making when set in an abstract context, although there was a greater appreciation of the model in its present real world form. Much of the underlying discussion pointed towards using the model to assist with policy evaluation. Suggestions were made concerning the introduction of other policy parameters into the model. On a cautious note, the lack of criticism levelled by the interviewees may show that their exposure to the RWOSM was too limited, not allowing them to comment adequately on the plausibility of the model's structure and equations. This may have stemmed from their exposure to a largely 'off the shelf' model.

Safety policy analysis was carried out to help better understand why the safety system of the firm behaved in a certain way. Policy experiments needed to be conducted to help design the best possible robust behaviour into the system. The only way to progress was to experiment with different policies, with the intention of designing a scenario suggesting how best to control both accident rates and safety costs in the firm.

Some of the more sensitive policy parameters identified in the behavioural testing of the GOSM were numerically modified in order to explore, and then design a better SMS. Five scenarios were chosen, simulated and examined. These scenarios all had distinctive strategies, with some emphasising risk control and others focusing on staffing policies. A comparative analysis of the alternative scenarios is shown in Table 1.

Output Metric	**Scenario 1 % Change Over Base Run**	**Scenario 2 % Change Over Base Run**	**Scenario 3 % Change Over Base Run**	**Scenario 4 % Change Over Base Run**	**Scenario 5 % Change Over Base Run**
Cumulative Accidents	0	-14	-15	-66	-89
Cumulative Safety Costs (£)	0	-8	0	-51	-65
Final Accident Rate	0	-26	-28	-83	-96
Final Monthly Safety Cost (£)	0	-21	-16	-70	-96

Table 1 Comparison of performance of key output metrics between alternative base run scenarios

The ‘base run’ scenario was called ‘business as usual’, and showed the safety management system of the firm continuing to gradually decline. Through heuristic experimentation the performance in each scenario improved. In the last scenario policies were suggested that could bring about a noticeable improvement in the accident rate as well as a reduction in the costs of running the SMS in the firm.

MODEL IMPLEMENTATION

There is a great deal of scope for further work using the occupational safety model. The study to date has finished with the evaluation of a range of plausible safety scenarios for one host firm. If the managers of this firm and other firms placed a high measure of faith in the ability of the model to suggest improved safety performance, and implemented the recommended policies, the model’s veracity could be readily tested.

Select and Implement Strategy

The managers of the host firm suggested that the model outputs had confirmed their suspicions that training, amongst a raft of other policies had the capacity to exert the most influence over the accident trend. They indicated that in particular, they were likely to increase the level of training within their firm. If the firm implemented this policy change, it could be revisited to if the recommended policies were adopted, and if so, did the model’s behaviour prediction hold true? Forrester and Senge (1980) describe this as the ultimate test of a system dynamics model, to see whether the desirable policies found after exploring a model, when implemented actually improve real system behaviour.

Calibrate/Evaluate Real World Stock/Flow Model

The RWOSM was tested in only one firm. This does not confirm that the model can be applied to all workplaces. All it indicates is that it was successfully tested in one. Further confidence in the model could be built if it was tested for a number of different workplaces and a range of plausible but different modes of safety behaviour could be exhibited. It could become evident as the model was tested in different workplaces that some of the structure may need to be overhauled, or even further structure introduced.

SUMMARY OF THE OCCUPATIONAL SAFETY MODELLING PROCESS

Using academic and practitioner literature, opinions of experts in the field of safety and personal assumptions, a generic system dynamics model of an occupational safety system was built. It was subsequently tested with data derived from an industrial setting. A number of alternative empirically based safety scenarios were explored and appropriate policy decisions illustrated. The opinions of users of the model were elicited in order to capture an understanding of the potential uses of the simulation as a pedagogic and decision-making aid. Suggestions have been made as to the further use of the model as an aid to firms across industry.

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