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A System Dynamics Analysis of the Westray Mine Disaster

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Abstract

This paper describes a system dynamics analysis of the Westray mine disaster. The paper examines the causal structure of the Westray system, including relationships that could have led to conditions that caused the fatal explosion at the mine. The value of simulation is its ability to capture a "mental model" of the safety system, which can stimulate discussion among safety experts as to the systemic causes of a disaster. By taking into account feedback loops and non-linear relationships, which is not possible with conventional root cause analysis, a dynamic model of the system provides insights into the complex web of causes that can lead to disaster and valuable lessons for organizational learning.

Keywords

System dynamics; Simulation; Safety management; Organizational accidents; Westray mine

Author Biography

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Introduction

Modern theories of "systemic safety" view disasters as the result of a breakdown in a complex socio-technical system that includes the physical facilities, the social interactions of the people involved, the information systems, and the "rules" or decision-making structures for the operation in question. Perrow (1984) coined the term "normal accidents" to describe the accidents that result from breakdown of a complex system for which no single cause can be found. Langewiesche (1998) drew on Perrow's work to argue that the Valujet disaster, in which 110 people died when flight 592 crashed into a Florida swamp, was unavoidable because it was "a 'system accident' which may lie beyond the reach of conventional solution." Roberts and Bea (2001) review what we have learned since Perrow's book was first published about what it takes to create a high-reliability organization. They recommend three policy levers to help build a high-reliability safety system: "Managers should aggressively seek to know what they don't know, design reward and incentive systems to recognize the cost of failure and the benefits of reliability, and communicate the big picture to everyone."

Supporting the notion that some accidents are "unavoidable," Kletz (1993) used information from industrial accidents to show that the "same accident" occurs over and over again. He suggests that organizations have no memory, and that accidents will recur unless special efforts are taken to keep the memory of accidents alive. One could also interpret this data to infer that the same system will continue to generate the same accidents.

Psychologists, who are interested in the behavioral aspects of safety, have provided a substantial body of literature on human error or "human factors" operating within a safety system. Reason (1990) provides a comprehensive review of research into human error, from which his analogy of a safety system's defenses being like a stack of Swiss cheese slices has been widely quoted. Under the "Swiss cheese" view of the system, a disaster would occur when the slices were juggled by a chain of events into such a configuration that the holes lined up by chance, representing a breach of the safety defenses that the solid part of the cheese slices otherwise provides. Until the disaster occurs, no one can see the holes in the safety system. Reason (1997) built upon his early work on human error to describe the concept of "organizational accidents," which acknowledges that accidents in complex systems have "multiple causes involving many different people at many different levels." He argues that "human error" is too limited a concept, and that managing the risks of organizational accidents must recognize that causes of accidents include both the precipitating action and the latent causes pre-existing in the system. Thus, Reason's "organizational accidents" are similar to Perrow's "normal accidents" and both are what I would call "system accidents."

Researchers such as Battmann and Klumb (1993) and Reason et al. (1998) have shown that risky human behaviors can be explained as being economically rational. A worker or manager will violate safety rules if doing so is expected to produce a positive outcome in terms of physical or psychological rewards. For example, meeting production targets results in a bonus for the manager and taking short cuts in standard operating procedures makes the task easier for the worker. The whole area of "behavioral safety" has become extremely popular, and books such as Geller (1996), Geller (2000), Krause (1996), and Peterson (1996) have made a significant contribution to the migration of behavioral safety ideas from research into practice at companies all over the world.

The more traditional economic approach to safety has been described by Adnett and Dawson (1998) as a trade off between production and accident prevention: "Accidents are assumed productive and can be avoided only by firms foregoing marketable output in favour of accident prevention." In this traditional model the firm operates to maximize profit, which occurs when the marginal cost of wages needed to attract workers willing to accept higher risk is equal to the marginal cost of providing a safer work environment and the cost of output lost as a result of accidents. Adnett and Dawson argued that the conventional economic approach was too narrow and simplistic, and could not explain the cyclical fluctuations in accident rates over time. They proposed that the accident rate should be a function of expenditures on accident prevention, workers efforts in production, industry sector relative wage, industry specific technological determinants of accident rates, and social cohesion of the workforce. They identified economic indicators as proxies for these variables, and used regression analysis of UK industry data to test their hypothesis. They were able to obtain results that were supportive of their proposed relationship, but were not able to draw firm conclusions because of inconsistencies in the results, which they attributed to poor data quality.

There has been considerable research into what is variously called "safety climate" or "safety culture." Summarizing this research, Hofmann and Stetzer (1998) say that "positive climates result when an organization's managers are committed to and personally involved in safety activities, provide and support safety training programs, and emphasized safety issues within the organization and when accident investigations are oriented toward problem solving and counseling." Hofmann and Stetzer's research showed that both safety climate and safety communications influenced the attribution of cause in an accident investigation. Workers in a positive safety climate with open communications were more willing to attribute cause to fellow workers or other internal workplace factors. The importance of a positive safety climate is also stressed by Geller (1996), who coined the term "total safety culture" to describe such a climate.

Brown et al. (2000) used data from a survey of steelworkers and their management to establish a correlation between factors influencing safe behaviors at work. The authors found evidence supporting a model in which "a chain reaction of technical and social constructs operate *through* employees to influence safe behaviors." The constructs included in this study were safety hazards, safety culture, and production pressures, which act on the attitudes and beliefs of the workers to influence their behaviors.

Many of the studies reported in the literature have sought to establish linear correlation between safety, whether measured by accident/incident rates or by questionnaire responses, and various other economic or behavioral factors. Similarly, the traditional approach to accident investigation follows a linear process of "root cause analysis," which ignores the effect of feedback and complex interactions between system variables. System dynamics is a tool that can be used to address these concerns. In this paper I will use a simplified model of the Westray mine system to illustrate how the methodology of system dynamics can be useful for understanding the behaviors of complex safety systems, which include feedback loops, time delays and non-linear relationships. I analyze the behavior of the dynamic model and, to the extent made possible by published information, compare its behavior to that of the actual Westray system. However, the reader should bear in mind that there are many causative mechanisms that can lead to a disaster such as that at Westray, and that a simplified causal model cannot possibly capture all of the technical, political or organizational factors that influence a real world system. Nevertheless, I hope to convince the reader that system dynamics modeling has much to offer in terms of improving our understanding of complex safety systems.

Although Perrow and Langewiesche would argue that systemic accidents are "beyond the reach of conventional solution," their thesis does not exclude the possibility of unconventional solutions! I suggest that approaches based on system dynamics modeling can provide new insights into the dynamics of complex safety systems which, over time, may lead to improvements in industrial safety management. System dynamic models are capable of showing how time lags in the system can cause poor safety performance to continue long after a management commitment to safety has been made, and the desired improvement may only appear years later if this commitment is maintained. In other words, system dynamic modeling highlights the importance of sustaining management commitment to safety at all times, even when current safety performance is good.

Synopsis of the Westray Mine Disaster

In 1987, Curragh Resources Inc. created subsidiary Westray Coal to operate a proposed coal mine that would create much-needed jobs in Plymouth, Nova Scotia, an economically depressed region of Canada. The coal seam in which the Westray mine was situated had claimed over 650 lives before the Westray mine was even proposed. In the report of the Westray Mine Public Inquiry, Richard (1996) notes that the mine had problems from the start, partly because of the technical difficulties inherent in the coal seam and partly because the company took shortcuts to get the mine into production as soon as possible. Problems included roof falls, accumulation of methane and coal dust, and unanticipated geological conditions.

Jobb (1994) suggests that although workers complained about the safety conditions in the mine, management did not listen, and neither did government. Some experienced workers left because of the poor working conditions, but many workers stayed because of their desperation for employment. Some government inspectors had concerns about the mine, but their concerns went unheeded by their superiors. Government politicians extended many incentives and subsidies to Westray to encourage production, including a take-or-pay contract for 275,000 tonnes per year of coal. A "take-or-pay" agreement means that the customer must pay for all production under the contract, up to the contractual amount, whether or not it is needed. However, if the supplier has production problems and cannot deliver under the contract, then the customer is relieved of the obligation to pay.

Leading up to the fatal explosion, Westray experienced many incidents that could have claimed lives but instead ended up as production losses. Ultimately, a source of ignition combined with an accumulation of methane and coal dust to cause the fatal explosion in the mine on May 9 1992, killing 26 miners. In the report of the Public Inquiry, eerily echoing the sentiments of Perrow and Kletz, Justice K. Peter Richard called Westray "a predictable path to disaster."

Dynamic Hypothesis and Boundary Selection

The dynamic hypothesis is that Westray management placed priority on "production at all costs" over safety in the mine, which created a chain of events leading to the disaster. Safety incidents, resulting from unsafe conditions in the mine, risky behavior on the part of miners, and management's tolerance of both unsafe conditions and risky behavior led to production losses. These losses reinforced management's drive to produce coal, which reduced their relative commitment to safety, creating a "vicious circle" that ultimately led to the fatal explosion in the mine. The behavior we would expect to see in the dynamic model would be an increase in management's drive for production in response to a growing backlog of orders, causing a decline in management commitment to safety over time, causing growth in the incident rate. When the incident rate reaches a "critical mass," an explosion becomes inevitable. Bird and Loftus (1976) provide support for this argument by demonstrating that a major accident is merely the “tip of the iceberg,” with many minor incidents hidden below the surface. The same concept held true at Westray, where a large number of incidents preceded the fatal explosion. Please note that in this paper I use the term “incident” in its broadest sense to mean an unplanned event that may or may not result in undesirable consequences, and an “accident” is defined as an incident with actual negative consequences. Negative consequences include all forms of loss, including safety, environmental, and production/quality losses.

The model boundary will be the mine, its management and employees, and the time period will be 100 - 500 weeks from the startup of the mine. Whereas the explosion actually occurred after the mine had been operating for about a year, simulation allows analysis of long-run system behavior.

Structural Model of the Westray System

Model Subsystems

For modeling purposes, the Westray Mine system can be conveniently broken down into four subsystems: Production, Human Resources, Safety and Mine Capacity. Figure 1 shows the model boundary and the information that passes between the four subsystems.

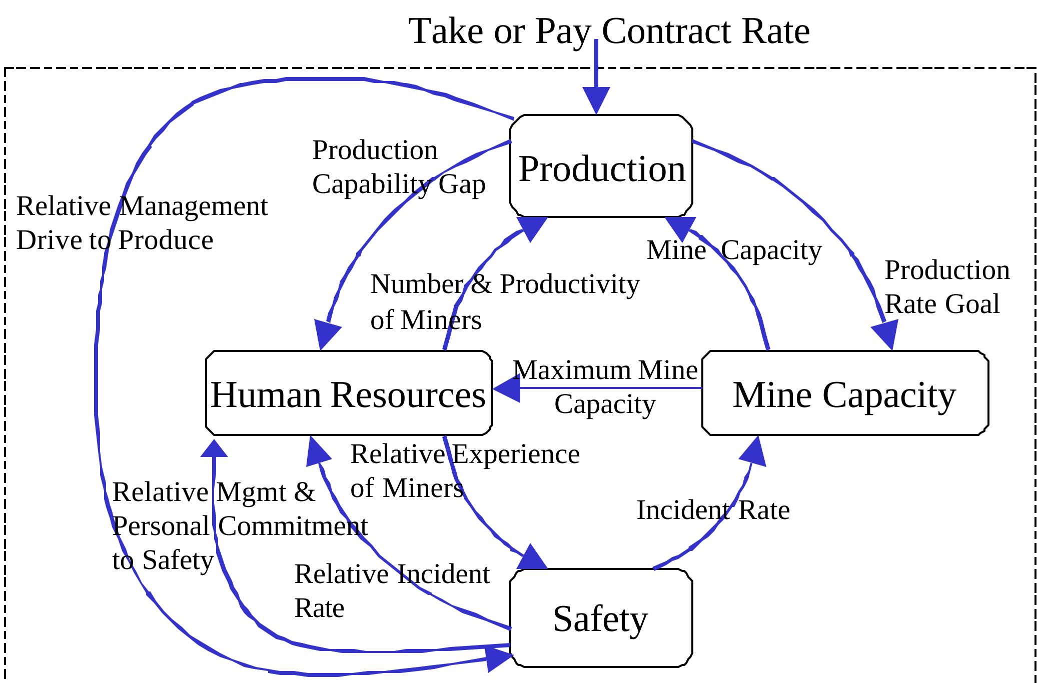


Figure 1: Subsystems of the Westray Mine Dynamic Model

In effect, the model boundary is drawn around the mine site and the management systems of the company operating the mine. The sections that follow describe the dynamic model for each of the four subsystems, however the reader is also referred to Figure 2, which provides a high-level overview of the causal structure.

In the causal loop diagram shown in Figure 2, we are primarily interested in the interactions between the safety system, which is largely behavioral, and the physical production system represented by the mine and the miners. These interactions are manifested in losses of production, departure of experienced workers, and the quality of experience that workers gain on the job.

In the discussion that follows, and throughout this paper, all model variables will be identified by Title Case.

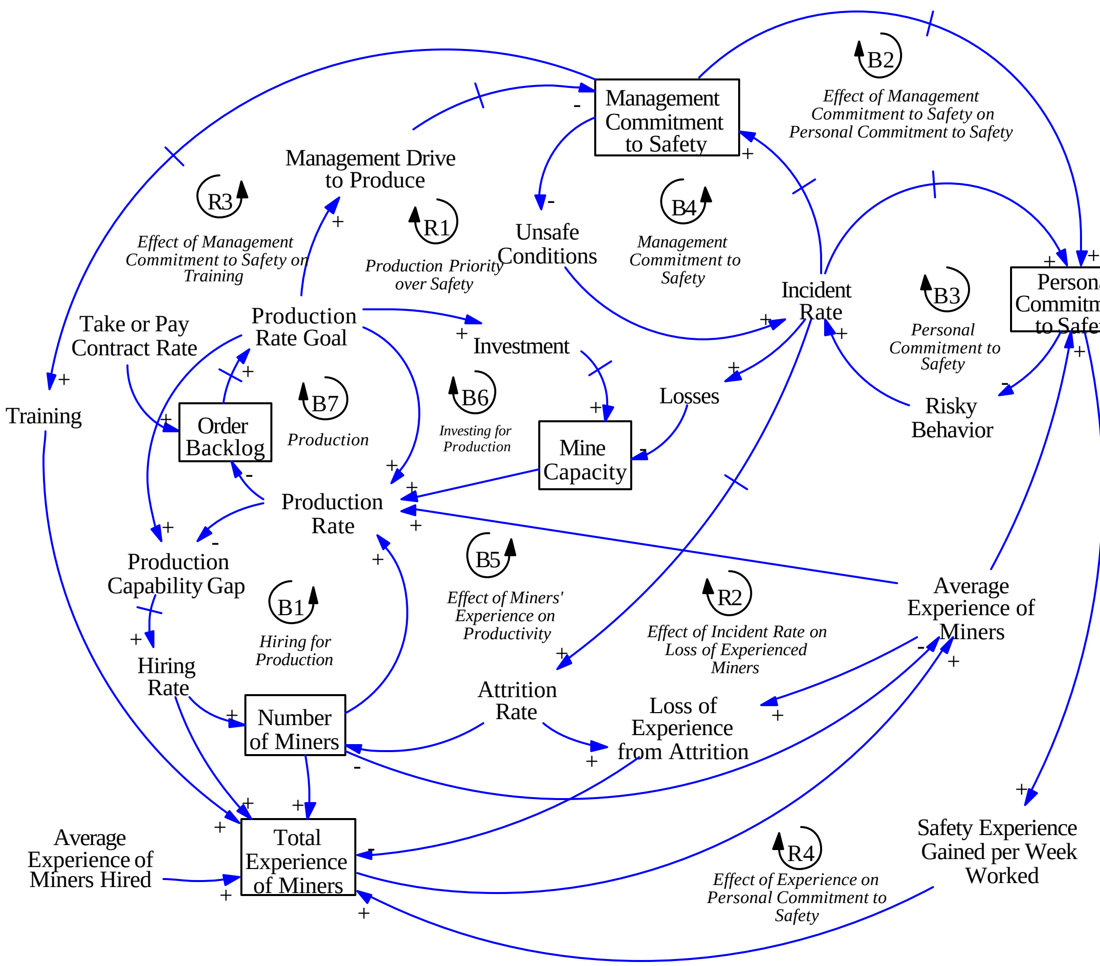


Figure 2: Overview of the Westray Mine Disaster Causal Structure

Mine Capacity Subsystem

The major determinant of Production Rate is Mine Capacity, which is caused by Investment in the mine. The Mine Capacity Subsystem, shown in Figure 3, represents the "Investing for Production" loop B6 shown in Figure 2. Mine Capacity is a stock that builds up by Investment in response to the Production Rate Goal, and is depleted by Losses from incidents.

Two balancing loops, B1 and B7 in Figure 2, sustain the Production Rate. Loop B6 causes investment in the mine in response to changes in the Production Rate Goal. Production increases to meet growing demand as long as management invests in mine expansion and hires more miners. Loop R1, "Production Priority over Safety," acts to reinforce management priority on production over safety, as losses from incidents will reduce mine capacity.

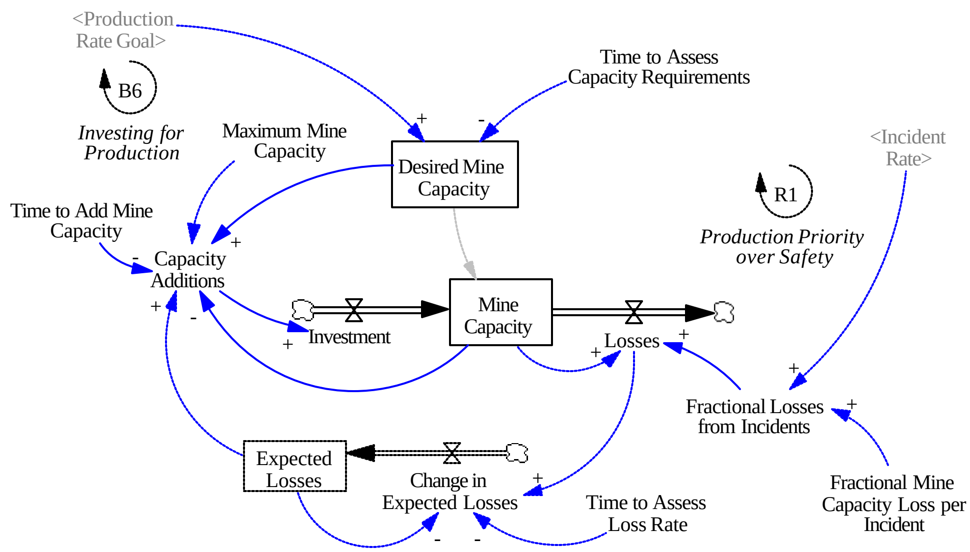


Figure 3: Mine Capacity Subsystem

The report of the Public Inquiry provides ample evidence that losses from incidents reduced the production capacity of the mine. For example, in March 1992, miners were compelled to abandon the Southwest 1 section of the mine as a result of unsafe ground conditions. Eventually, this section of the mine was abandoned entirely. The Public Inquiry report and the miners' testimony show that major roof falls occurred regularly, severely impacting the production capacity of the mine. As Comish (1993) wryly comments, "I swear, if the newspapers or TV had reported every rockfall that occurred, that's all that would have been in the news."

In the model, the initial Mine Capacity at time zero is set at the Desired Mine Capacity, which is calculated by smoothing the Production Rate Goal over the Time to Assess Capacity Requirements. Maximum Mine Capacity is set at 7000 tonne/week, about 27% above the Take or Pay Contract Rate of 5500 tonne/week. With a 52-week Time to Add Mine Capacity and no losses, 95% of desired mine capacity would be added over three years, which is consistent with the evidence at Westray that it took three years from start of mine development to start up of the mine.

Production Subsystem

The financial incentive to produce coal was caused by Westray's "take-or-pay" contract with a local power company, which obligated the purchaser to pay for all coal produced, even if it was not needed. This contract is the main driver of the production subsystem, and is modeled by the exogenous variable Take or Pay Contract Rate.

The stock and flow structure of the Production Subsystem, which is based on the inventory control and order fulfillment archetypes described in Sterman (2000), is shown in Figure 4. It is typical of any such system to be found in the manufacturing or mining industry. The Production Rate Goal is set to meet the Expected Order Rate, correct the Order Backlog and restore Desired Inventory (Balancing loop B7 in Figure 2).

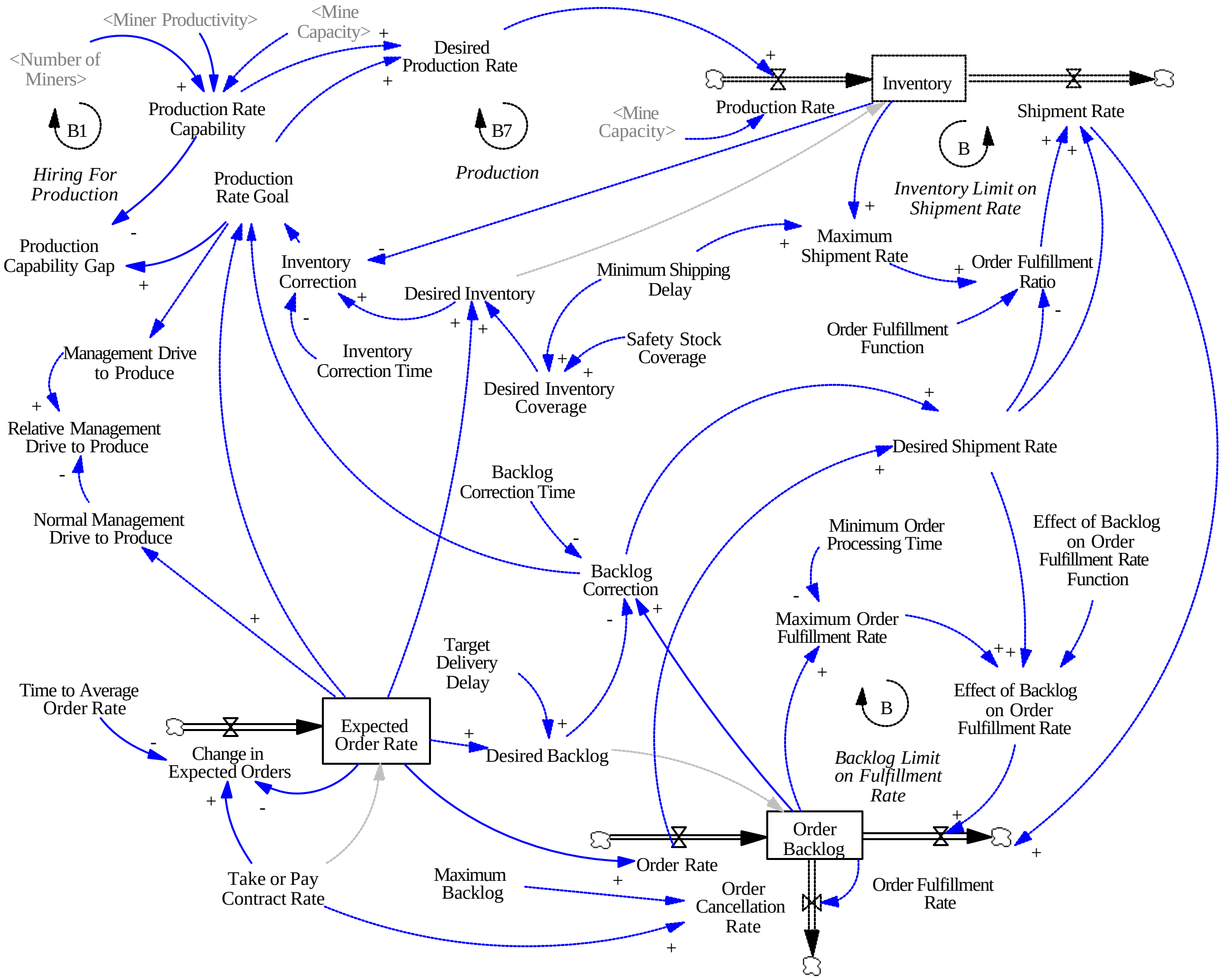


Figure 4: Production Subsystem

The stock of Inventory is increased by the Production Rate, and decreased by the Shipment Rate. Although the Production Rate Goal is set to meet orders, restore inventory and eliminate the backlog, the Desired Production Rate is limited in practice by Production Rate Capability (Miner Productivity times the Number of Miners) and the physical Mine Capacity.

The Inventory Correction is set equal to the difference between the Desired Inventory and the actual Inventory divided by the Inventory Correction Time. Desired Inventory Coverage is set at four weeks, being the sum of Safety Stock Coverage (two weeks) and the Minimum Shipping Delay (two weeks), and the Inventory Correction Time is set at eight weeks. These are "typical industry values," consistent with values used by Sterman for similar systems, and are not specific to the Westray system.

The balancing loop entitled "Inventory Limit on Shipment Rate" in Figure 4 is needed to prevent negative inventory and to provide a realistic response to shipment rate when the desired shipment rate gets close to the maximum. Following the practice of Sterman (2000), a user-defined function, called the Order Fulfillment Function, has been specified to model this response. The parameters of this function are the same as those used by Sterman.

The Order Backlog is modeled in a similar way to that of Inventory. The main difference is that production, inventory, and shipments represent physical materials whereas order rate, order backlog and order fulfillment represent information. The set up of the equations is similar, and the same user-defined function is used for the order backlog function as for the order fulfillment function. The validity of this model for the Westray system is supported by the fact that Westray could accumulate orders under the take or pay agreement during the current year provided that they had proven in the previous year that the mine would be capable of full production (Richard, 1996).

Human Resources Subsystem

The Human Resources subsystem includes the process for hiring miners, the process for tracking their work experience and the effect of this experience on productivity. The stock and flow structure shown in Figure 5 is an adaptation from Sterman (2000), involving a co-flow of two stocks, one being the number of miners and the other being the total experience of the miners.

The Number of Miners and Mine Capacity determine the Production Rate, so management hires (or fires) more miners to close the Production Gap (Balancing loop B1). This structure stabilizes when enough miners have been hired to raise Production Rate to close the Production Gap. The experience of the miners also influences the Production Rate, and as shown in Figure 5, both hiring and on-the-job experience will increase their collective experience. The Hiring Rate is driven by the Production Capability Gap, with the Number of Miners being limited by the Maximum Mine Capacity. Experienced miners are lost by attrition, and the Attrition Rate increases if the miners perceive the Incident Rate to be higher than normal. Miners gain experience by spending time on the job, but lose experience through a decay process that mirrors memory loss.

Although Westray recruited some experienced coal miners initially, these were only a minority and several of them subsequently resigned because of working conditions in the mine. Many of the miners only had experience in hard rock mines, in which conditions are quite different than those found in a coal mine. The Public Inquiry found that Westray management hired inexperienced miners and provided little or no training. This suggests that a relatively low value would be appropriate for the exogenous variable Average Experience of Miners Hired and that the variable Increase in On the Job Experience should be function of both Safety Experience Gained per Week Worked and the amount of Training provided by management. The amount of Training is assumed to be a smoothed function of the product of Relative Management Commitment to Safety and the observed Experience Gap. In loop R3, the "Effect of Management Commitment to Safety on Training," the more management is committed to safety, the more experience is gained from training provided, and the more productive the miners become. This productivity improvement reinforces management's commitment. Loop R4 is similar, except in this case it is Personal Commitment to Safety that is reinforced by the Relative Experience of Miners.

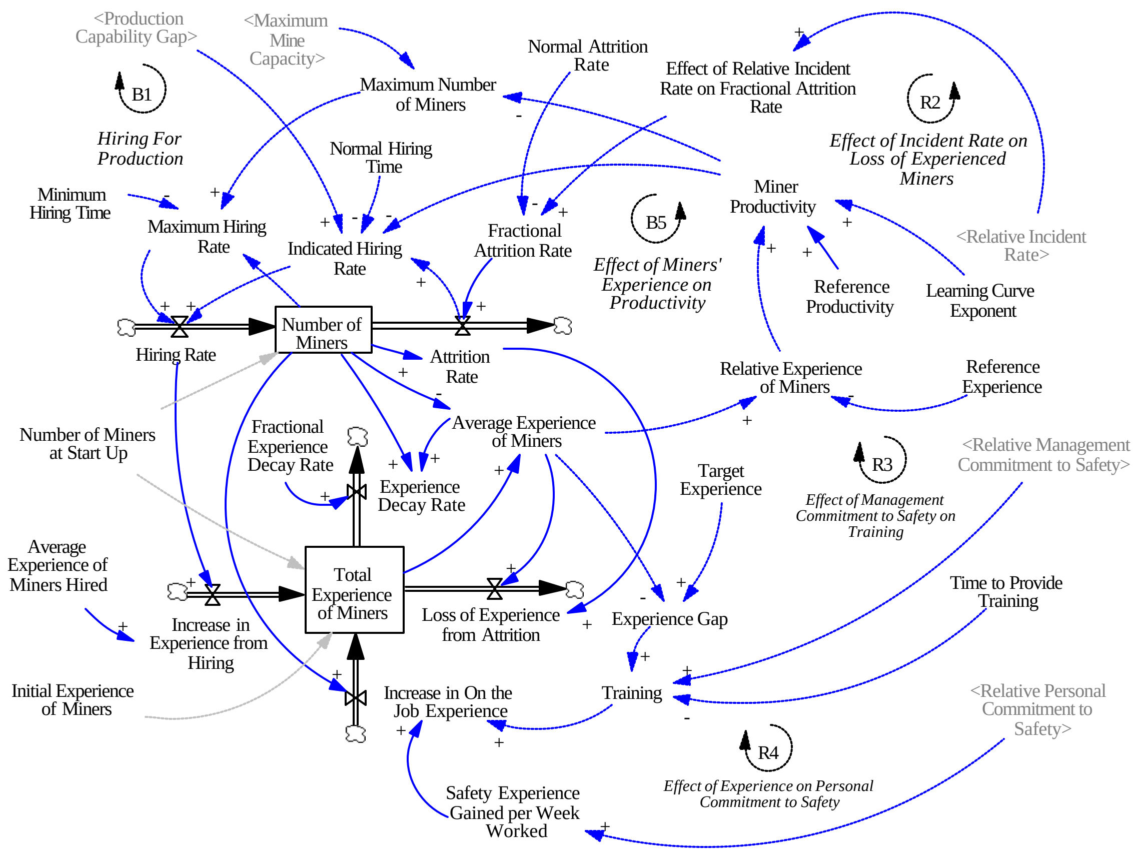


Figure 5: Human Resources Subsystem

Feedback loop R2, the "Effect of Incident Rate on Loss of Experienced Miners," causes loss of production through loss of experienced miners. Lower experience leads to lower Personal Commitment to Safety, more Risky Behavior and a higher Incident Rate. With more incidents, the Attrition Rate goes up as experienced miners leave the company. At facilities with poor safety performance and a high Incident Rate, experienced workers will not tolerate an unsafe working environment indefinitely, and will eventually leave for a job in a safer environment. Having gained experience working in safe well-managed mines, many experienced miners chose to leave Westray taking their experience and personal safety commitment with them. Replacement miners were generally hired locally with little or no relevant experience. By late 1991, only 15 of 70 miners on staff were certified to work in a coal mine. Experienced miners left the company, and novices took their place (Jobb, 1994).

Although data relating incident rates to employee attrition are limited, Allen (1981) shows that absenteeism is higher in plants with high occupational injury and illness rates. This relationship is modeled by assuming that the Fractional Attrition Rate will be normal if the Incident Rate is less than or equal to normal, but will increase in proportion to the Incident Rate if the Incident Rate is higher than normal.

The Number of Miners at Start Up is set at 70 so that the Production Rate Capability will be in equilibrium with the Production Rate Goal at time-zero. The Initial Experience of Miners is set at 100 weeks/person, the same as the Reference Experience, and the Average Experience of Miners Hired is set at 50 weeks/person. However, it is assumed that management's objective is to train the miners to a level just above the Reference Experience, so that a Target Experience of 101 weeks/person is set for the workforce as a whole.

Safety Subsystem

Westray was not the first disaster, nor unfortunately is it likely to be the last one, caused by an explosion in a coal mine. Accumulations of coal dust, methane and a source of ignition were readily available to cause the fatal explosion in the Westray mine. The number of fatalities was caused by the size of the explosion and the number of miners underground at the time. All of the immediate causes of the fatal explosion appear to have been incidents that can be linked to low commitment to safety on the part of management, as shown in Figure 6. The details in Figure 6 are based on the findings of the Public Inquiry (Richard, 1996).

Sterman (2000) argues that it is better to capture the important feedback loops in a system than to pursue unnecessary complexity or detailed definition. Thus, the complex network of causes shown in Figure 6 was not included in the dynamic model because the underlying causal structure can be modeled by a single variable called Unsafe Conditions.

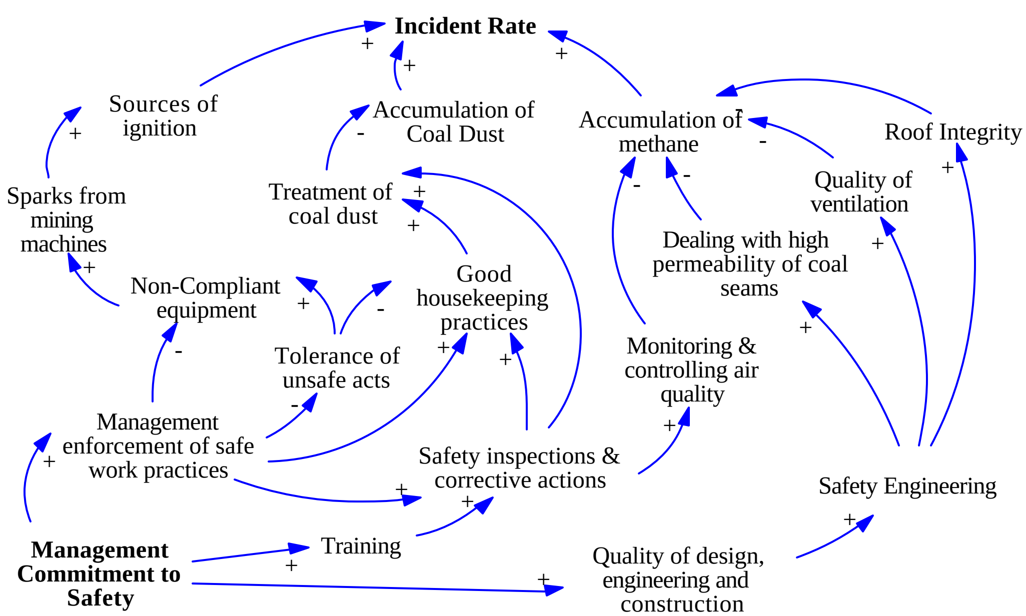


Figure 6: Immediate Causes of the Westray Disaster

In any hazardous operation, such as that at the Westray mine, there is a critical reinforcing loop that I will call "Production Priority over Safety" (Loop R1 in Figure 2). Like all reinforcing loops, this can act as either a “vicious circle” or as a “virtuous circle” (Safety Priority over Production) depending on management’s relative commitment to safety. Normally, management must balance priorities between production and safety. This can be a difficult task as the pressure for production invariably leads to a reduction in the relative priority that management gives to safety, and a gradual lowering of the personal commitment to safety on the part of individual workers. Since workers’ jobs may depend on fitting in with the expectations set by management, workers will respond to the drive for production by engaging in more risky behavior to get the job done, meet deadlines and satisfy production quotas. With a lower commitment to safety, management takes fewer actions to eliminate Unsafe Conditions and the Incident Rate increases both as a result of the Unsafe Conditions and from the Risky Behavior of the workers.

At Westray, there is evidence that pressure for production was high. In their testimony to the Westray Mine Public Inquiry, United Steelworkers of America (1996) devoted a full section of their written submission to the “pressure for production.” They documented a lengthy list of operational decisions that “reflected the assignment of a higher priority to production than to safety” on the part of management. In the report of the Public Inquiry, Justice Richard found that “management avoided any safety ethic and apparently did so out of concern for production imperatives” and that “Westray was to produce coal at the expense of worker safety.” He went on to say that “Management's drive to produce and its failure to advocate safety in the workplace rendered any harmonization of production and safety difficult. Thus, Westray failed both to meet production demands and to address safety concerns.”

In loop R1, as the Incident Rate increases so do Losses, which cause reductions in Mine Capacity. At Westray, these losses included roof falls, high methane concentrations, and equipment failure. As losses mounted the production rate fell and management’s drive to produce increased, exacerbated by the pressure created by the “take or pay” contract – no production, no pay!

In a more safety-conscious company than Westray, loop R1 would operate as a virtuous circle with management maintaining a high relative commitment to safety at all times. In such a company, with a positive safety climate, workers would know that it would be better to shut down production to deal with an unsafe condition, because management expects it of them, than to continue unsafe operation. Although production may suffer in the short term while safety deficiencies are corrected, fewer Unsafe Conditions and less Risky Behavior ultimately lead to a lower Incident Rate and fewer Losses.

The stock and flow structure for the Safety Subsystem, shown in Figure 7, comprises several loops: B2, Effect of Management Commitment to Safety on Personal Commitment to Safety; B3, Personal Commitment to Safety; B4, Management Commitment to Safety; R1, Production Priority over Safety, and R4 Effect of Experience on Personal Commitment to Safety.

The fundamental construct for each of the “safety commitment” structures is what Sterman calls a “sea anchor and adjustment.” This structure is used to represent a process by which people “grope” towards a proper quantity – in this case the “right” amount of commitment to safety. The model assumes that both management and miners start with a “normal” commitment to safety, which then changes in response to various pressures. Management Commitment to safety responds to pressure from Relative Management Drive to Produce and from the Relative Incident Rate.

The miners’ Personal Commitment to Safety responds to pressure from Management Commitment to Safety, from their Relative Experience, and from the Incident Rate. Unsafe Conditions are assumed to be inversely proportional to Relative Management Commitment to Safety, while Risky Behavior on the part of miners is assumed to be inversely proportional to their Relative Personal Commitment to Safety.

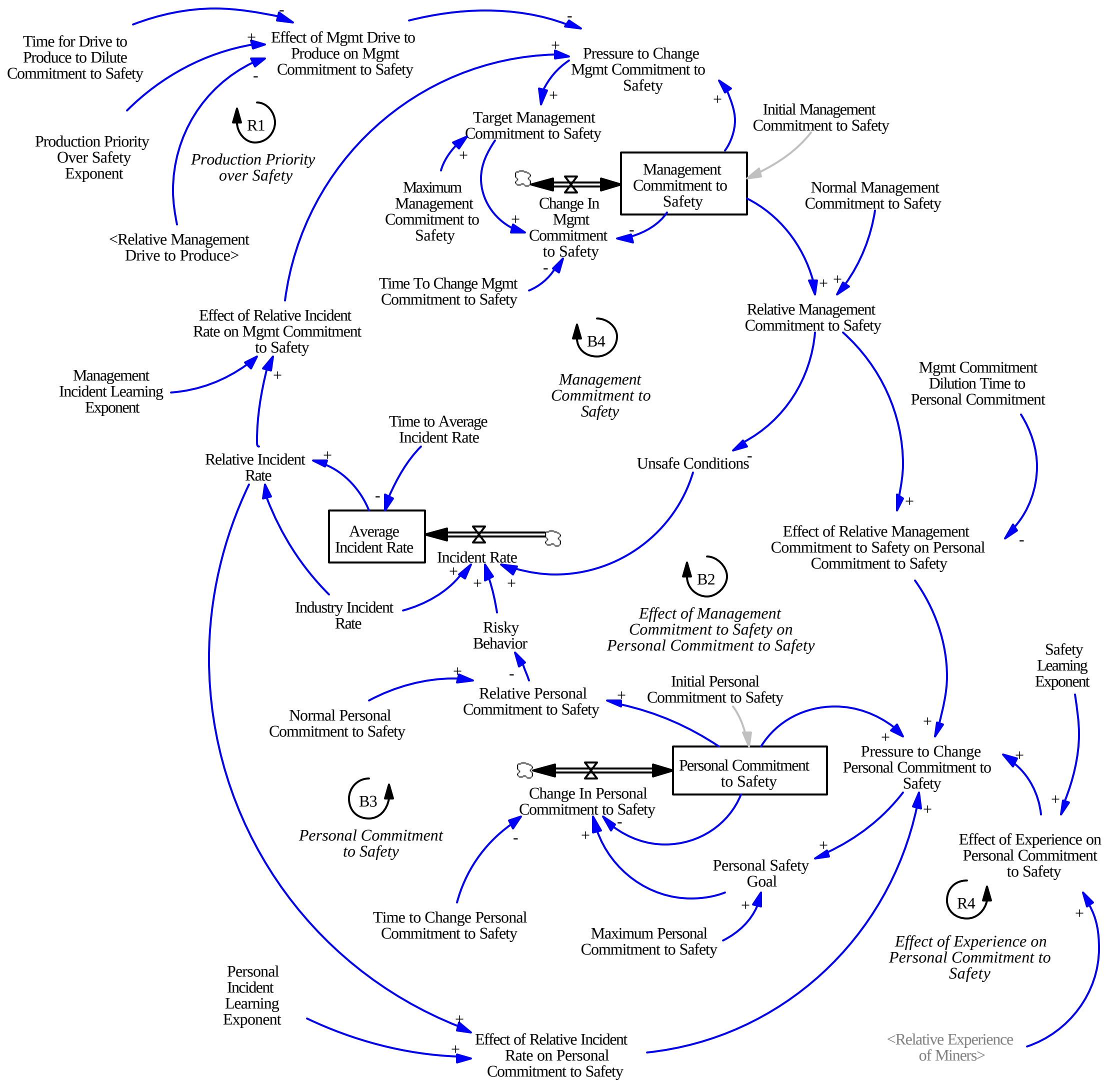


Figure 7: The Safety Subsystem

The vicious circle aspect of putting production priorities over those of safety is ultimately balanced by the effect of incidents on management's commitment to safety. Thus, there is some level of poor safety performance at which any management will take action to reduce losses from incidents, because it simply makes economic sense to do so. Thus, Management Commitment to Safety can act directly through Unsafe Conditions or indirectly through the worker's Personal Commitment to Safety. In other words, worker safety is led by example from management.

Even when management has a low relative commitment to safety, there is a balancing loop created by the individual worker's personal commitment to safety, which is shown in the "Personal

Commitment to Safety" loop B3. If workers perceive the Incident Rate to be higher than normal, they will increase their personal commitment to safety so as to minimize risk of injury. As their commitment to safety increases, workers engage in less risky behavior which results in fewer incidents. Fewer incidents lead to a lower Relative Incident Rate, which acts to balance the loop.

In balancing loop B4, "Management Commitment to Safety," which captures what Reason (1997) calls the "dangers of the unrocked boat," there is a tendency for management commitment to safety not to be maintained when the Incident Rate falls. Seeing a low Incident Rate, management assumes that safety is not an issue and turns their attention to other priorities. Thus, it is important that management recognizes this loop and counteracts it by maintaining their commitment to safety at all times, despite competing priorities and apparently "good" safety performance. Further, the Board of Directors can act as an external policy lever to apply pressure on Management Commitment to Safety.

The report of the Public Inquiry provides support for feedback loop R4, the "Effect of Experience on Personal Commitment to Safety." At Westray, the miners' inexperience caused them to disregard the dangers inherent in an underground coal mine, to perform unsafe tasks and to take shortcuts in their work. Until a person experiences or observes a narrow escape from an accident, workplace hazards and risk of personal injury tend to be abstract concepts! In the culture of risk-taking at Westray, the low Personal Commitment to Safety caused low Safety Experience Gained per Week Worked, lowering the Average Experience of Miners and reinforcing the low commitment. Counterbalancing this, in loop B5, management responds to higher incidents with a higher commitment to safety, causing them to implement Training programs that increases the workers' experience. The greater the miner's experience, the greater his or her personal commitment to safety.

Although not explicitly included in the dynamic model of the Westray system, it is worth discussing the influence of politicians and regulators, which was important in reinforcing the low management commitment to safety at the mine. The Westray mine was a much-needed investment in an economically depressed region of Nova Scotia. Public pressure to create jobs caused political pressure to operate the mine, even though the economic fundamentals were shaky to say the least. The government of Nova Scotia and the government of Canada responded by providing generous incentives to operate the mine. Management of Curragh Resources Inc., the owner of the Westray mine, was found by the Public Inquiry to have intimidated both the politicians and the regulators by threatening to abandon the mine project if their financial demands were not met. I would submit that the political support for mine operation, and the reluctance of regulators to enforce safety regulations, acted to reinforce Westray management's priority to production over safety.

Model Validation and Testing

The validity of the proposed model for the system at Westray is supported by the information contained in Richard (1996), Jobb (1994) and Comish (1993). Interviews with safety professionals with respect to their perceptions of the Westray disaster have elicited comments such as, "it was a disaster waiting to happen," "there was no safety system," and "safety infractions were everywhere!"

I have discussed a case study of the Westray Mine disaster with several classes in the Faculty of Management at the University of Calgary. When asked to identify the causes of the disaster, students invariably come up with a causal structure that is similar to the one described here. In other words, there appears to be ample evidence in the facts of the Westray Mine disaster to support the causal structure described in this paper. However, I recognize that a simplified model cannot possibly capture all of the causative mechanisms at play in a complex safety system such as Westray. For example, the model does not include any causative factors corresponding to geological conditions in the mine. It could be argued that the Pictou coal seam in which the Westray Mine was located is inherently unstable and loaded with methane, so that no amount of management commitment to safety would have prevented the explosion. Another likely causative factor that is not explicitly included in the model is the production bonus system under which the miner's operated. At the Public Inquiry, experts testified that a bonus pay scheme based solely on production was not conducive to safety in the mine. However, in defense of the model, it could be argued that the geological conditions are covered by the Unsafe Conditions variable and that the production bonus system is one of the mechanisms by which Management Commitment to Safety influences Personal Commitment to Safety. Nevertheless, a model will always have limitations.

The model was subjected to extreme condition testing and it was found to generally behave as expected. For example, Figure 8 shows what happens if the model is run with the Number of Miners at Start Up equal to one and an Industry Incident Rate of zero.

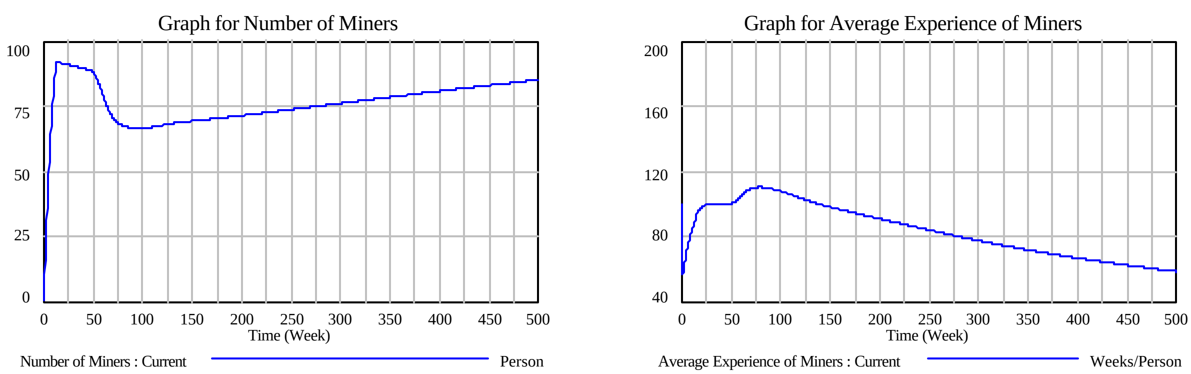
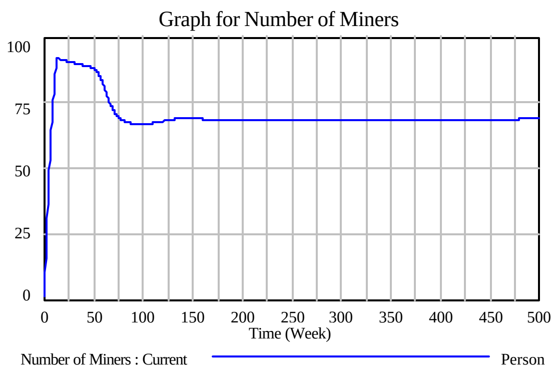


Figure 8: Mine starts up with just one miner, but no incidents

An interesting observation from this scenario is that management hires workers as quickly as they can, as expected, but because production immediately falls behind schedule the backlog builds and management commitment to safety falls. Since the new workers hired are inexperienced, they require training. However only a minimal amount of training is provided because management is not strongly committed to safety. Why should they be? – There are no incidents! Consequently, Personal Safety Commitment falls to zero (graph not shown) and Average Experience of Miners falls well below the Target Experience. As shown in Figure 8, hiring 85 miners eventually eliminates the order backlog, but as we shall see below, this is more than would have been needed if training had been provided.

The next case shows what happens if the model is set up with just one miner to start, but with the Industry Incident Rate set at 0.1 per week instead of zero. Figure 9 shows that the model settles down with 69 miners hired and the Target Experience level achieved. The difference in this case is that both management and miners respond to the Incident Rate with an increased Management and

Personal Commitment to Safety respectively, Training is provided, and the Incident Rate is eventually brought under control.



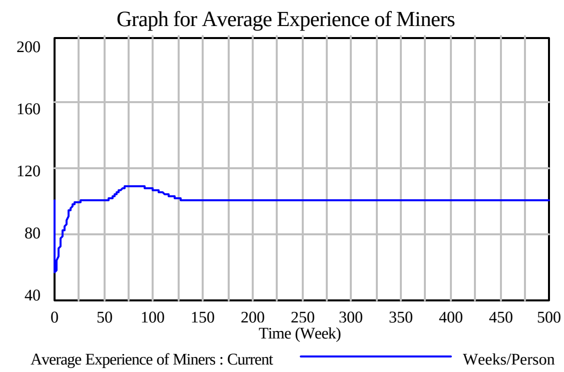


Figure 9: Management responds to incidents by providing training, which increases experience and miner productivity, thereby reducing staffing requirements

Validating a model of a complex organizational system like that at the Westray mine is quite difficult because data is lacking for so many of the relationships in the model. For many of these relationships I have used a simplified power law relationship, which is typically used to model "learning curves" or "utility functions." Even though a 0.4 power law exponent appears reasonable, this simplifying assumption should be borne in mind when interpreting the results of the model.

Discussion of Results

Model Performance with No Incidents

The model was first tested with no incidents to ensure that it starts in equilibrium with no Order Backlog. The model was run for a period of 500 weeks. Although we are interested in behavior during the first year of operation, because the Westray mine explosion actually occurred about one year after startup, we are also interested in the long run behavior of the system.

Under the "no incidents" condition, the model is in production equilibrium and simply "flat-lines" with shipments equal to orders, mine capacity constant, and both inventory and backlog at stable constant values.

The "base case" values of the model parameters are given in the model equation listing shown in the appendix.

Model Performance with "Normal" Losses from Incidents

Next, the model was run with a "normal" Industry Incident Rate of 1 per week, with Fractional Mine Capacity Loss per Incident set at 0.01. Although the model can be run with a random value for the Incident Rate, which one could argue might produce more "realistic" results, using a constant value gives a much clearer picture of the underlying dynamics.

Introducing losses from incidents to the model dramatically changes its behavior, as losses in mine capacity now cause a growing Order Backlog and an increase in Management Drive to Produce. However, as shown in Figure 10, these are brought under control within a year and are back to normal within two years.

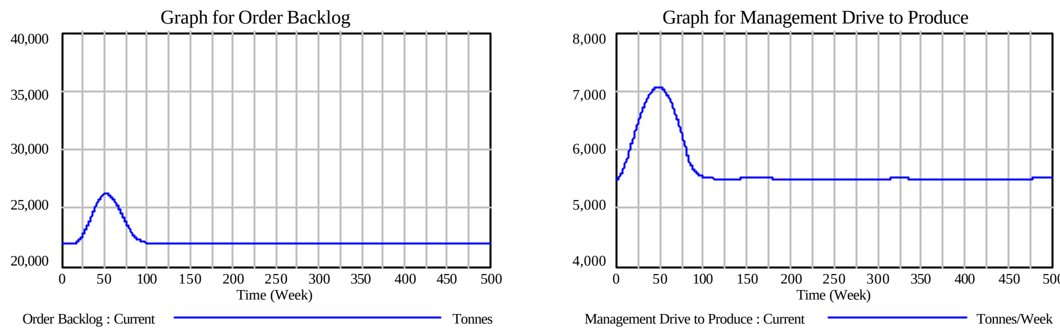


Figure 10: Management's drive to produce responds to the order backlog

The effect of increasing Management Drive to Produce is to cause Management Commitment to Safety to fall with a consequent effect on the miner's Personal Commitment to Safety, shown in Figure 11. Note that management commitment falls sooner and more precipitously than personal commitment, because the effect of management commitment on personal commitment is delayed, and because personal commitment tends to increase in response to the increasing Incident Rate. Once the Order Backlog has been dealt with, production pressures ease and Management Commitment to Safety rises as management responds to bring the Incident Rate under control.

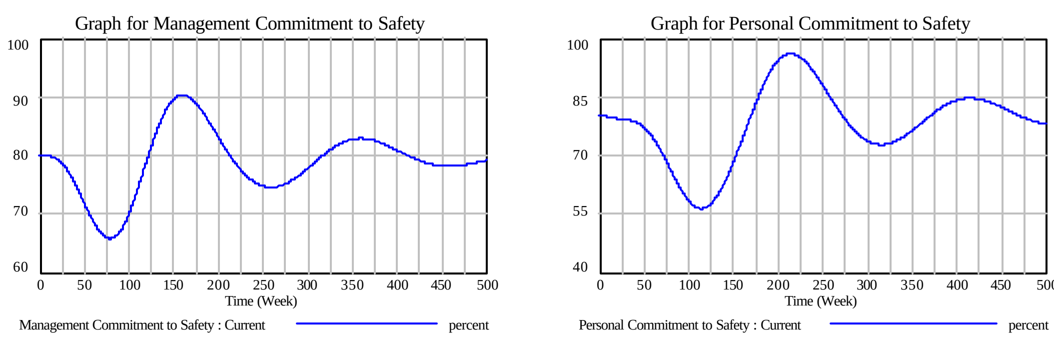


Figure 11: Management commitment to safety falls, pulling personal commitment with it

Notice that Personal Commitment to Safety does not peak until one year after the peak in Management Commitment to Safety. This reflects the typical worker's "show me" response to management safety initiatives. The oscillations in commitment over a ten-year period could either be interpreted as over-sensitivity in the model, or as management mounting "safety campaigns" in response to a rising Incident Rate in any given year and then easing off on these campaigns as the Incident Rate improves in subsequent years. My own experience would suggest that management does indeed launch renewed safety campaigns following significant losses from an incident, and that this higher level of commitment wanes as "things get back to normal."

The response to the initial decline in Commitment to Safety is that the Incident Rate initially increases and Mine Capacity initially falls because of losses from incidents, as shown in Figure 12.

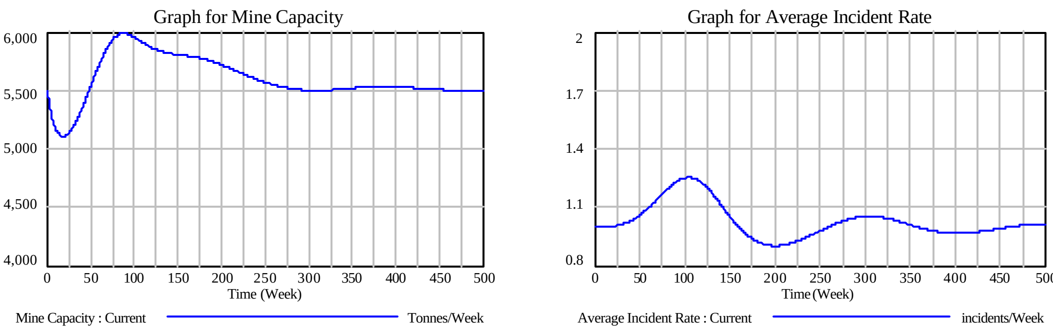


Figure 12: Mine capacity falls as the incident rate increases

Management responds with investment in Mine Capacity, but overshoots the required capacity because of over-estimation of expected Losses. The Incident Rate peaks at 100 weeks, leading to the strong management response noted above, and then falls to its lowest point after a delay of as long as 50 weeks after Management Commitment to Safety has reached its peak.

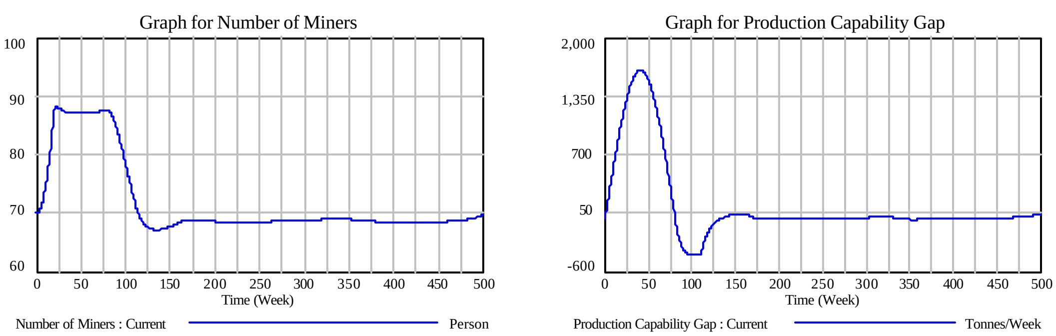


Figure 13: Miners are hired (and fired!) to close the production gap

Figure 13 shows that more miners are hired in response to the declining production capability as losses mount. The increased staffing raises the Production Rate and eliminates the Production Capability Gap within 80 weeks, and then hiring stops. However, as the situation returns to normal, staffing is reduced through attrition and layoffs until production capability is again aligned with production requirements.

It is interesting to see that time delays in the system cause the Incident Rate to fluctuate for several years, even though the underlying system has not changed. The fluctuations in Incident Rate and Management Commitment to Safety over the years are a result of system dynamic responses to the Incident Rate stimulus at time zero. In the real world system there would be many stimuli at different times, instead of just one step change at time zero. It is easy to see how real world system performance could fluctuate at random, making it difficult to detect system responses to management initiatives.

Model Performance with High Losses from Incidents

The next set of results shows model performance under a "worst case" scenario, which I expect was the case at Westray. The model parameters are the same as in the previous two runs, except that the Incident Rate has been increased to four incidents per week and the Fractional Mine Capacity Loss per Incident has been increased to 0.05. In this scenario, we model only 100 weeks of operation because the Incident Rate would otherwise rise exponentially until the simulation terminates. This is analogous to the mine blowing up when the Incident Rate crosses a critical threshold.

Under this scenario, the Order Backlog grows towards the maximum value and Management Commitment to Safety drops to very low levels (Figure 14).

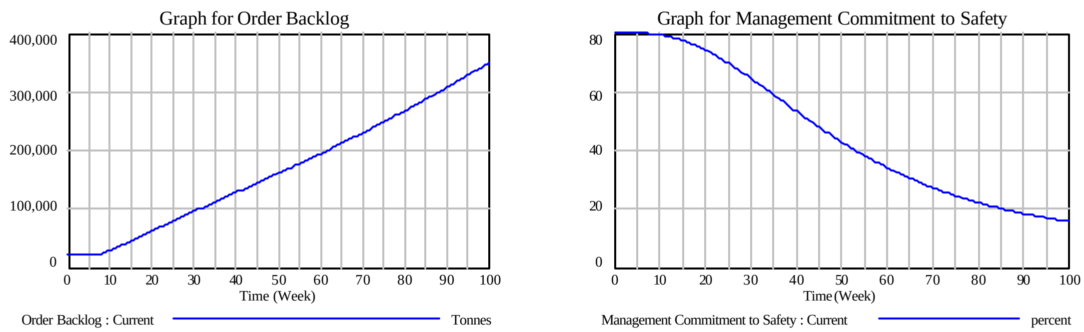


Figure 14: Higher losses create a higher backlog and safety commitment plunges

The miners' Personal Commitment to Safety stays high initially because of the high Incident Rate, as they seek to minimize the risk of injury. However, as the Incident Rate accelerates and production pressure increases, the miners are forced by pressure from management to reduce their commitment to safety (Figure 15).

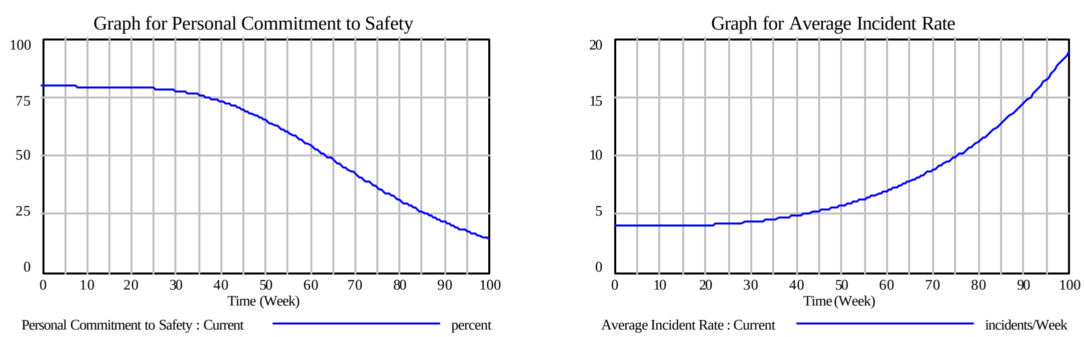


Figure 15: Safety commitment falls under a "high loss" scenario

The combination of a higher number of incidents and a higher loss in mine capacity per incident causes a dramatic decline in Mine Capacity, which falls to one third of its original value by the end of the year. Mine expansion, which has a long lead-time, is simply unable to keep up with the losses. Management hires additional miners in an attempt to maintain production, but the new hires are inexperienced and less productive so even more are required (Figure 16).

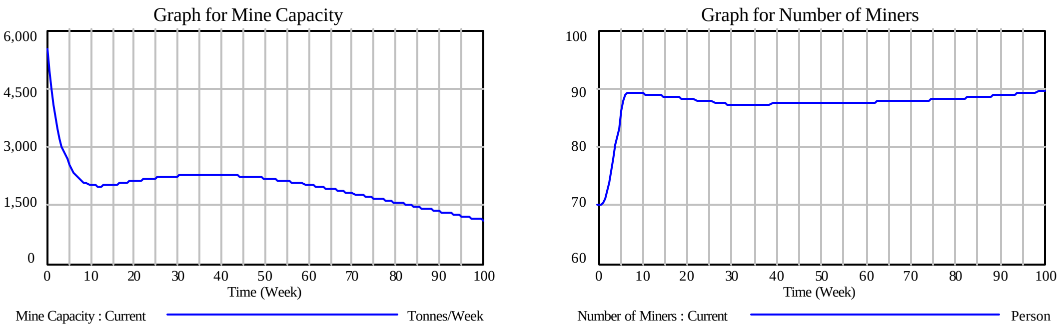


Figure 16: Mine capacity and workforce under "high loss" scenario

Figure 17 shows that management initially provides training to the new hires, which is a response to the drop in Average Experience of Miners. This training is initially effective, because it is reinforced by the miners' personal commitment to safety, and it restores average experience to the target level. However, after about the twenty-fifth week the Average Experience of Miners starts to fall in response to declining Personal Commitment to Safety. The decline in Average Experience of Miners accelerates because the Training response from management is now significantly weakened by the low Management Commitment to Safety. This falling Average Experience of Miners has the effect of causing the Number of Miners to *increase* with time, with the perverse result that more miners will be in the mine when it explodes. Evidence from the Public Inquiry suggests that this is exactly what happened at Westray.

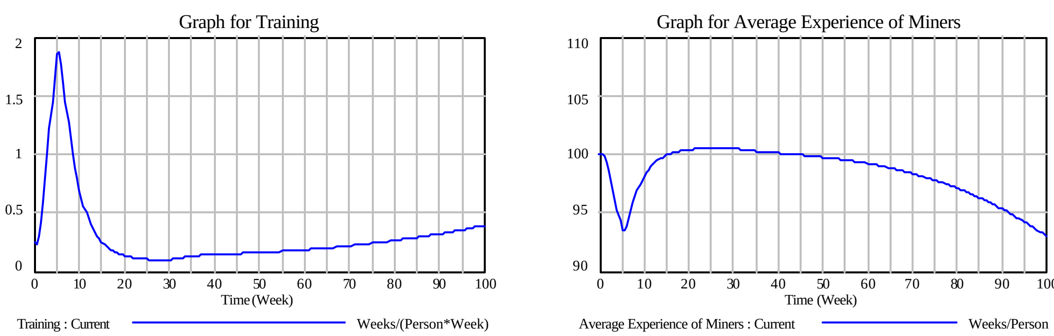


Figure 17: Early training efforts restore experience of miners initially

Leverage Point: Effect of Putting Safety First

The value of the Production Priority over Safety Exponent determines the strength of the relationship between Management Drive to Produce and Management Commitment to Safety. My hypothesis is that at Westray the value for this exponent was much higher than at more safety-conscious organizations. This scenario examines what happens if the link between Management Drive to Produce and Management Commitment to Safety is weakened by setting the Production Priority over Safety Exponent to a much lower value, say 0.01. If the exponent were set at zero, the link would be broken completely and the order backlog would have no effect whatsoever on the Incident Rate. Interestingly, if the exponent is set at 0.3, Incident Rate exponential growth is arrested but both the Incident Rate and Management Commitment to Safety oscillate continuously, with Incident Rate between the range 15 - 50 incidents/week with a period of about 150 weeks. Note that this scenario is again based on a 500-week time frame to show the long-term effects on the system. All other parameter values used in the previous "worst case" simulation are maintained, including the high Incident Rate of four per week and the high Fractional Mine Capacity Loss per Incident of 0.05.

In this scenario, the Order Backlog and Management Drive to Produce rise as before, but not as precipitously because the critical feedback loop has been weakened, and management remains committed to safety (Figure 18).

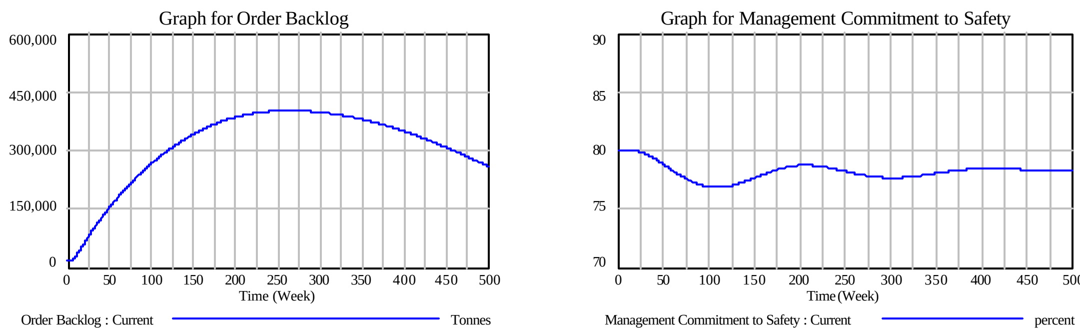


Figure 18: High losses create a backlog, but management remains committed to safety

Personal Commitment to Safety stabilizes and the Incident Rate remains under control (Figure 19). The Incident Rate remains higher at the end of 500 weeks, but will eventually return to the "normal" rate of 4 incidents per week after about 900 weeks. This is a consequence of the long delays inherent in such a complex system.

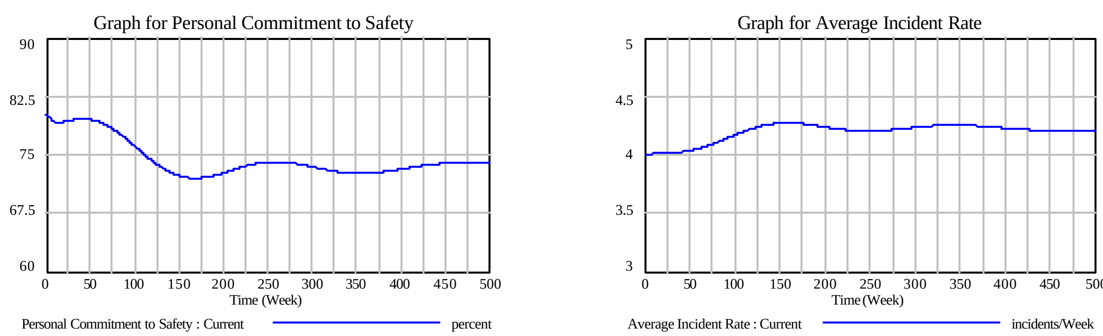


Figure 19: With "Safety First," personal commitment to safety stays high

While Mine Capacity still drops precipitously, as in the previous scenario, it eventually recovers as the high Incident Rate is brought under control, more miners are hired to close the Production Capability Gap, and Investment in the mine restores capacity (Figure 20).

Because the assumptions for the "worst case" scenario are extreme in terms of the size of losses, it is likely that the mine would be deemed uneconomical and abandoned well before the end of the

500 week simulation period. However, the simulation shows that the mine could have been operated safely up to the time that the closure decision was made. The implication for the real world system at Westray is that although the high incident rate at Westray may have caused the venture to be an economic disaster in terms of production losses, it did not have to be a catastrophe in terms of human life.

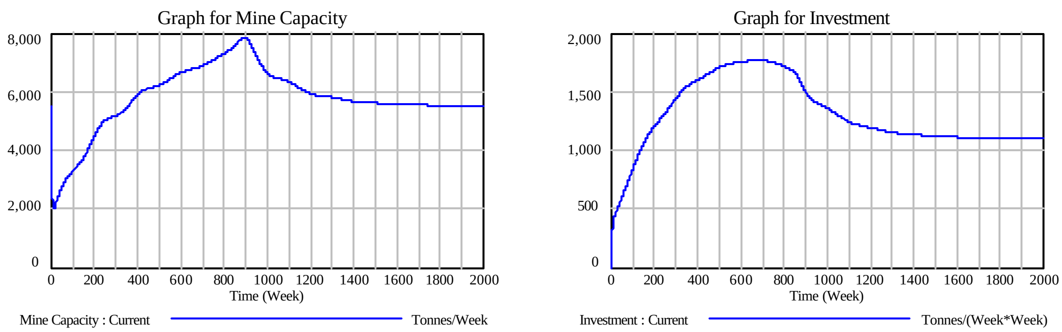


Figure 20: It takes 30 years for investment in the mine to restore lost capacity

Conclusion

The simulation results for the “high loss” scenario show how the incident rate at the Westray mine could rapidly accelerate in response to management placing a much higher priority on production over safety. With the incident rate accelerating rapidly at Westray, it is not too difficult to imagine that concurrent incidents involving a high concentration of methane, coal dust and a source of ignition from a defective machine could have led to the fatal explosion.

The simulation results also show the positive benefits to be derived from a “safety first” policy that significantly weakens the linkage between Management Drive to Produce and its effect on Management Commitment to Safety. The results show that even a “worst case” scenario can be brought under control. While this “safety first” policy may be open to criticism as being too obvious - “Of course, management commitment to safety will reduce incidents!” or “Isn’t everyone committed to safety?” - it was not obvious enough to the management of Westray and Curragh Resources Inc. As a result, 26 miners died and the company went bankrupt.

I offer three lessons for organizational learning from this analysis of the Westray mine disaster:

1. **Accidents are outputs of the system.** A system produces both the intended outputs and the accidental outputs, and management is responsible for the quality control of both. At the Westray Mine Public Inquiry, some testimony tried to blame the miners for various safety infractions that could have led to the explosion. However, these arguments did not sway Justice Peter Richard, who concluded that “Management failed, the inspectorate failed, and the mine blew up.” In other words, management is responsible for the system and the system failed. In general, I believe that we will reduce the risk of system accidents only when we approach these accidents as being a consequence of the behavior of the *system as a whole*, and not of the individual components such as people, procedures or equipment.
2. **It takes years of commitment to build a safety culture.** There are large delays in the build up and decay of “safety culture,” as measured by Management and Personal Commitment to

Safety. Consequently, the current incident rate may be a poor indicator of long term performance because the system may only respond to safety improvements after a long elapsed time. The implication of this observation is that management should not waiver from its long-term commitment to safety, whether or not the current incident rate is good or bad.

3. **Safety should take priority over production.** While it may be "normal" or "natural" for an organization to respond to production pressures as its first priority, it should be the role of management, especially senior management and the Board of Directors, to make *safety* the organization's first priority. Safety commitment is not self-sustaining, and so leverage must be applied to maintain it. Without safety, there can be no assurance of production. Production issues can be dealt with once safety has been addressed. With safety as the first priority, reinforcing feedback loops will operate as virtuous circles instead of vicious circles. As commitment to safety increases, losses from incidents will fall, productive experiences will grow, and production performance will improve.

Although the dynamic model has demonstrated its capability to exhibit reasonable behavior under four different scenarios: no incidents, low incidents, high incidents, and "safety first," the results should be used with caution. The results from any simulation model are open to criticism of the validity of the assumptions underlying the model. The true natures of the functions that are used to model human behavior are, of course, most open to debate since many of the relationships have not been empirically tested. However, as the old saying goes, all models are wrong but only some models are useful! I would argue that the Westray dynamic model is useful because it is grounded in the causal relationships established by the Westray Mine Public Inquiry and in system archetypes that have been researched by Sterman and others. Further, I would argue that the ability of system dynamic modeling to take into account time delays and non-linear relationships marks a significant advance over the more traditional root cause analysis method for understanding organizational accidents. Interpreted with caution, the results of this analysis of the Westray Mine disaster are encouraging and serve as a good demonstration of the potential use of system dynamic modeling to improve our understanding of the safety management of complex systems.

Since it is possible to adapt the model presented here to fit other industrial safety systems, further work is recommended to apply the learning from this study to other systemic safety incidents such as the NASA Challenger disaster or the Union Carbide Bhopal disaster. There are also many opportunities to improve and verify the causal relationships in the Safety Subsystem model. Opportunities for enhancement could include structures to capture the organization's ability to learn from incidents by implementing an incident investigation system. Other enhancements could be driven by new findings emerging from organizational accident research.

In conclusion, this paper has shown how system dynamics modeling can provide valuable insights into the behavior of a complex safety system like that of the Westray mine disaster. Organizations are encouraged to build models of their own safety systems, and to use these as tools for continuous improvement. Looking to the future, as we build on our knowledge of the behavior of complex socio-technical systems, we can perhaps look forward to a time in which "normal" accidents can indeed be prevented.

Acknowledgement

I acknowledge the thoughtful, detailed and helpful comments made by the anonymous reviewers of this paper, which have guided me towards a much better result than I would have attained without their direction.

Appendix: Stock and Flow Model Equations

The model was implemented in Vensim Version 4.1, supplied by Ventana Systems.[1] The model equations are grouped according to each subsystem in the listing below.

1. Mine Capacity

Capacity Additions = Expected Losses + (min(Desired Mine Capacity, Maximum Mine Capacity) - Mine Capacity)/Time to Add Mine Capacity …1-1

Change in Expected Losses = (Losses - Expected Losses)/Time to Assess Loss Rate …1-2

Desired Mine Capacity = smooth(Production Rate Goal, Time to Assess Capacity Requirements) …1-3

Expected Losses = INTEG (Change in Expected Losses, 0) …1-4

*Fractional Losses from Incidents = Incident Rate * Fractional Mine Capacity Loss per Incident* …1-5

Fractional Mine Capacity Loss per Incident = 0.01 per incident …1-6

Investment = max(Capacity Additions, 0) …1-7

*Losses = Fractional Losses from Incidents * Mine Capacity* …1-8

Maximum Mine Capacity = 7000 tonne/week …1-9

Mine Capacity = INTEG (Investment-Losses, Desired Mine Capacity) …1-10

Time to Add Mine Capacity = 52 weeks …1-11

Time to Assess Capacity Requirements = 13 weeks …1-12

Time to Assess Loss Rate = 6 weeks …1-13

2. Production

Backlog Correction = (Order Backlog - Desired Backlog)/Backlog Correction Time …2-1

Backlog Correction Time = 8 weeks …2-2

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[1] Ventana Systems, Inc., 60 Jacob Gates Road, Harvard, MA 01451 http://www.vensim.com/

Change in Expected Orders = (Take or Pay Contract Rate - Expected Order Rate)/Time to Average Order Rate …2-3

*Desired Backlog = Expected Order Rate * Target Delivery Delay* …2-4

*Desired Inventory = Expected Order Rate * Desired Inventory Coverage* …2-5

Desired Inventory Coverage = Minimum Shipping Delay + Safety Stock Coverage …2-6

Desired Production Rate = min(Production Rate Capability, Production Rate Goal) …2-7

Desired Shipment Rate = Order Rate + Backlog Correction …2.8

Effect of Backlog on Order Fulfillment Rate = Effect of Backlog on Order Fulfillment Rate Function (Maximum Order Fulfillment Rate/Desired Shipment Rate) …2-9

Effect of Backlog on Order Fulfillment Rate Function …2-10
The relationship for this user-defined function is the same as that for the Order Fulfillment Function, equation 2-24.

Expected Order Rate = INTEG (Change in Expected Orders, Take or Pay Contract Rate) …2-11

Inventory = INTEG (Production Rate-Shipment Rate, Desired Inventory) …2-12

Inventory Correction = (Desired Inventory - Inventory)/Inventory Correction Time …2-13

Inventory Correction Time = 8 weeks …2-14

Management Drive to Produce = Production Rate Goal …2-15

Maximum Backlog = 104 weeks …2-16

Maximum Order Fulfillment Rate = Order Backlog/Minimum Order Processing Time …2-17

Maximum Shipment Rate = Inventory/Minimum Shipping Delay …2-18

Minimum Order Processing Time = 2 weeks …2-19

Minimum Shipping Delay = 2 weeks …2-20

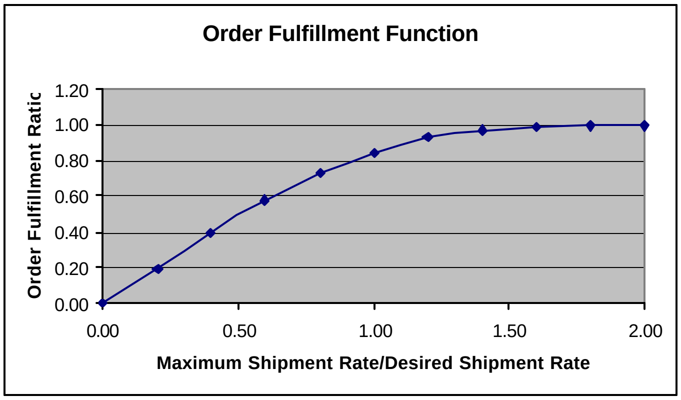
Normal Management Drive to Produce = Expected Order Rate …2-21

Order Backlog = INTEG (Order Rate - Order Fulfillment Rate - Order Cancellation Rate, Desired Backlog) …2-22

*Order Cancellation Rate = IF THEN ELSE(Order Backlog > Maximum Backlog * Take or Pay Contract Rate, Take or Pay Contract Rate, 0)* …2-23

Order Fulfillment Function …2.24

A user-defined function from Sterman (2000) defined as follows:



*Order Fulfillment Rate = Shipment Rate * Effect of Backlog on Order Fulfillment Rate* …2-25

Order Fulfillment Ratio = Order Fulfillment Function (Maximum Shipment Rate/Desired Shipment Rate) …2-26

Order Rate = Expected Order Rate …2-27

Production Capability Gap = Production Rate Goal-Production Rate Capability …2-28

Production Rate = min(Desired Production Rate , Mine Capacity) …2-29

*Production Rate Capability = min(Miner Productivity * Number of Miners, Mine Capacity)* …2-30

Production Rate Goal = max(0, Expected Order Rate + Backlog Correction + Inventory Correction) …2-31

Relative Management Drive to Produce = Management Drive to Produce/Normal Management Drive to Produce …2-32

Safety Stock Coverage = 2 weeks …2-33

*Shipment Rate = Desired Shipment Rate * Order Fulfillment Ratio* …2-34

Take or Pay Contract Rate = 5500 tonne/week …2-35

Target Delivery Delay = 4 weeks …2-36

Time to Average Order Rate = 4 weeks …2-37

3. Human Resources

*Attrition Rate = Number of Miners * Fractional Attrition Rate* …3-1

Average Experience of Miners = Total Experience of Miners/Number of Miners …3-2

Average Experience of Miners Hired = 100 weeks/person …3-3

Effect of Relative Incident Rate on Fractional Attrition Rate =max(Relative Incident Rate,1) …3-4

*Experience Decay Rate = Number of Miners * Average Experience of Miners * Fractional Experience Decay Rate* …3-5

Experience Gap = max(Target Experience - Average Experience of Miners, 0) …3-6

*Fractional Attrition Rate = min(Normal Attrition Rate * Effect of Relative Incident Rate on Fractional Attrition Rate, 1)* …3-7

Fractional Experience Decay Rate = 0.001 per week …3-8

Hiring Rate = min(Indicated Hiring Rate, Maximum Hiring Rate) …3-9

*Increase in Experience from Hiring = Hiring Rate * Average Experience of Miners Hired*…3-10

*Increase in On the Job Experience = Number of Miners * Safety Experience Gained per Week Worked * Training* …3-11

*Indicated Hiring Rate = Attrition Rate + Production Capability Gap/(Miner Productivity * Normal Hiring Time)* …3-12

Initial Experience of Miners = 100 weeks/person …3-13

Learning Curve Exponent = 0.4 …3-14

*Loss of Experience from Attrition = Attrition Rate * Average Experience of Miners* …3-15

Maximum Hiring Rate = max(0,(Maximum Number of Miners - Number of Miners)/Minimum Hiring Time) …3-16

Maximum Number of Miners = Maximum Mine Capacity/Miner Productivity …3-17

*Miner Productivity = Reference Productivity * (Relative Experience of Miners)^Learning Curve Exponent* …3-18

Minimum Hiring Time = 1 week …3-19

Normal Attrition Rate = 0.001 per week …3-20

Normal Hiring Time = 8 weeks …3-21

Number of Miners = INTEG (Hiring Rate - Attrition Rate, Number of Miners at Start Up)…3-22

Number of Miners at Start Up = 70 person …3-23

Reference Experience = 100 weeks/person …3-24

Reference Productivity = 80 tonne/person per week …3-25

Relative Experience of Miners = Average Experience of Miners/Reference Experience …3-26

Safety Experience Gained per Week Worked = Relative Personal Commitment to Safety …3-27

*Total Experience of Miners = INTEG (Increase in Experience from Hiring + Increase in On the Job Experience - Experience Decay Rate - Loss of Experience from Attrition, Number of Miners at Start Up * Initial Experience of Miners)* …3-28

Target Experience = 101 weeks/person …3-29

Time to Provide Training = 4 weeks …3-30

*Training = Experience Gap * Relative Management Commitment to Safety / Time to Provide Training* …3-31

4. Safety Subsystem

Average Incident Rate = INTEG ((Incident Rate - Average Incident Rate)/Time to Average Incident Rate, Incident Rate) …4-1

Change In Mgmt Commitment to Safety = (Target Management Commitment to Safety - Management Commitment to Safety)/Time To Change Mgmt Commitment to Safety …4-2

Change In Personal Commitment to Safety = (Personal Safety Goal - Personal Commitment to Safety)/Time to Change Personal Commitment to Safety …4-3

Effect of Experience on Personal Commitment to Safety = (Relative Experience of Miners)^Safety Learning Exponent …4-4

Effect of Mgmt Drive to Produce on Mgmt Commitment to Safety = Smooth(1/(Relative Management Drive to Produce)^Production Priority Over Safety Exponent, Time for Drive to Produce to Dilute Commitment to Safety) …4-5

Effect of Relative Incident Rate on Mgmt Commitment to Safety = (Relative Incident Rate)^Management Incident Learning Exponent …4-6

Effect of Relative Incident Rate on Personal Commitment to Safety = (Relative Incident Rate)^Personal Incident Learning Exponent …4-7

Effect of Relative Management Commitment to Safety on Personal Commitment to Safety = smooth(Relative Management Commitment to Safety, Mgmt Commitment Dilution Time to Personal Commitment) …4-8

*Incident Rate = Industry Incident Rate * (Unsafe Conditions + Risky Behavior)/2* …4-9

Initial Management Commitment to Safety = 80 percent …4-10

Initial Personal Commitment to Safety = 80 percent …4-11

Industry Incident Rate = 1 incident per week …4-12
"Industry Incident Rate" can be set at zero to remove the effect of Incident Rate on the system, otherwise it is set at the required value.

Management Commitment to Safety = INTEG (Change In Mgmt Commitment to Safety, Initial Management Commitment to Safety) …4-13

Management Incident Learning Exponent = 0.4 …4.14

Relative Management Commitment to Safety = Management Commitment to Safety /Normal Management Commitment to Safety …4-15

Maximum Management Commitment to Safety = 120 percent …4-16

Maximum Personal Commitment to Safety = 120 percent …4-17

Mgmt Commitment Dilution Time to Personal Commitment = 13 weeks …4-18

Normal Management Commitment to Safety = 80 percent …4-19

Normal Personal Commitment to Safety = 80 percent …4-20

Personal Commitment to Safety = INTEG (Change In Personal Commitment to Safety, Initial Personal Commitment to Safety) …4-21

Personal Incident Learning Exponent = 0.4 …4.22

Personal Safety Goal = min(Pressure to Change Personal Commitment to Safety, Maximum Personal Commitment to Safety) …4-23

*Pressure to Change Mgmt Commitment to Safety = Management Commitment to Safety * Effect of Relative Incident Rate on Mgmt Commitment to Safety * Effect of Mgmt Drive to Produce on Mgmt Commitment to Safety* …4-24

*Pressure to Change Personal Commitment to Safety = Personal Commitment to Safety * Effect of Relative Management Commitment to Safety on Personal Commitment to Safety * Effect of Relative Incident Rate on Personal Commitment to Safety * Effect of Experience on Personal Commitment to Safety* …4-25

Production Priority Over Safety Exponent = 0.4 …4-26
Set at zero to remove the effect of "Drive to Produce" on management commitment to safety, otherwise set at 1 or at some intermediate value to reflect the degree to which production commitment overrides safety commitment.

Relative Incident Rate = IF THEN ELSE(Industry Incident Rate = 0 , 1, Average Incident Rate/Industry Incident Rate) …4-27

Relative Personal Commitment to Safety = Personal Commitment to Safety/Normal Personal Commitment to Safety …4.28

Risky Behavior = 1/Relative Personal Commitment to Safety …4.29

Safety Learning Exponent = 0.4 …4.30

Target Management Commitment to Safety = min(Pressure to Change Mgmt Commitment to Safety, Maximum Management Commitment to Safety) …4-31

Time to Average Incident Rate = 4 weeks …4-32

Time To Change Mgmt Commitment to Safety = 13 weeks …4-33

Time to Change Personal Commitment to Safety = 13 weeks …4-34

Unsafe Conditions = 1/Relative Management Commitment to Safety …4-35

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