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A System Dynamics View of Safety Management in Small Construction Companies

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***Abstract:** Due to unique characteristics of small construction companies, safety management is comprised of complex problems. This paper aims to better understand the complexity and dynamics of safety management in small construction companies. A system dynamics (SD) model was built in order to capture the causal interdependencies between factors at different system levels (regulation, organization, technical and individual) and their effects on safety outcomes. Various tests were conducted to build confidence in the model's usefulness to understand safety problems facing small companies from a system dynamics view. A number of policies were analyzed by changing the value of parameters. The value of a system dynamics approach to safety management in small construction companies is its ability to address joint effects of multiple safety risk factors on safety performance with a systems thinking perspective. By taking into account feedback loops and non-linear relationships, such a system dynamics model provides insights into the complex causes of relatively poor safety performance of small construction companies and improvement strategies.*

***Keywords:** Construction safety, Small businesses, System dynamics, Modeling*

I. INTRODUCTION

Small companies, which are defined as those that employ 20 or fewer employees [1], make up the majority of construction companies in the European Union [2], the USA [3], Australia [4], and New Zealand [5]. According to the MBIE, the number of small construction firms was 48557 in New Zealand in 2014, making up over 98% of the construction industry. There have been consistent reports that small construction companies (SCCs) have a higher safety risk than larger construction companies [6-9]. For example, McVittie et al. [10] found that injury frequency decreases as business size increases. Jeong [11] also reported that SCCs have more fatal and nonfatal injuries than larger ones.

It has been recognized that SCCs, compared with large ones, have special problems with regard to safety management. For example, from an economic point of view, they are more fragile financially [12]. Tight profit margins and limited market share make them less willing to invest time and economic resources on safety [12-14]. This is especially the case when SCCs experience the lows of the business cycle. As a result, safety is gradually marginalized as they put emphasis on client satisfaction, workloads, and cash flow which are vital for business success [15]. A lack of managerial and information resources is another significant issue for SCCs. Gillen et al. [16] pointed out that small and un-union companies lack some of the resources that are available to large and union contractors.

SCCs are often run by owner-managers, who have to manage many different tasks simultaneously, such as bidding, planning, administration, etc. [17]. This situation, together with financial pressure and a lack of safety knowledge and management skills, makes owner-managers less committed to safety [14, 18, 19]. As a consequence, production is always placed as a priority over safety and unsafe behaviors are acceptable on site due to a lack of safety climate. Employees of SCCs are less likely to be provided with safety training. This can be consequential because construction workers are less educated than other industries [20] and a lack of safety knowledge can undermine their ability to work safely on hazardous sites.

Aforementioned safety problems are often discussed separately without placing them in the whole system and taking into account effects of interrelationships between various subsystems on safety performance. In fact, safety problems that plague SCCs are complex, involving multiple actors (regulators, clients, owner-managers, supervisors and workers, etc.). It is not effective to address safety management without considering other aspects of running a small business [1]. Due to the complexity, intervention programs that are developed for large companies have often been found ineffective for small ones [14, 21, 22]. Thus, a better understanding of the complexity of safety management in SCCs becomes important.

Therefore, the goal of this paper is to advance an understanding of the complexity of safety management in SCCs by examining the interactive relationships between factors of different subsystems and their effects on safety performance. A systems dynamics (SD) approach is applied in this paper to build, test and simulate a system dynamics model of safety management in SCCs.

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II. SYSTEM DYNAMICS

System dynamics (SD), which was founded by Forrester in MIT [23], is a methodology that can be used to understand, analyze and model complex real-world problems. Unlike traditional approaches that are concerned with linear cause-and-effect, system dynamics is conceptually based on the feedback concept and focuses on circular, interlocking, and sometimes time-delayed relationships among system components [24]. As an aspect of systems theory, it considers all concepts in the real system as continuous quantities interconnected in feedback loops and circular causality [24].

An SD analysis typically involves the following five steps [24]: (1) problem articulation, (2) formulation of dynamic hypothesis, (3) formulation of a simulation model, (4) testing, and (5) policy design and evaluation.

The first model-building step is to clearly identify the purpose for a model and the problem that it aims to solve. This step is concerned with specifying the problem of concern and determining appropriate scope and resolution of the model. The second stage of model building focuses on determining the structure of the model in a qualitative way. The tool of causal loop diagram (CLD) is used to map causal links among these variables with arrows from a cause to an effect [24]. Reinforcing and balancing feedback loops and delays are basic blocks in the CLDs. Briefly, a reinforcing loop is a structure that feeds on itself to generate exponential growth and collapse, in which the growth or collapse continues at an ever-increasing rate (see Fig. 1). If the trend is ascending, the reinforcing loop will accelerate the growth. If the trend is descending, it will accelerate the decline. In contrast, a balancing loop produces a goal seeking behavior. As shown in Fig. 2, it intends to reduce a gap between a current state and a desired state. It moves a present state towards a desirable target regardless whether the trend is descending or ascending. Delays represents the time that elapses between cause and effect [25]. Once an initial dynamic hypothesis is developed, a modeler needs to transfer the causal loop diagram into a stock and flow diagram in which the type of variables (i.e., stock or flow), equations between these them, initial conditions are determined. The stock and flow diagram provides a quantitative description of the system. As shown in Fig. 3, stocks represent accumulation and thus characterize the state of the system, as a result of difference between inflow and outflow. After the model is built, it is necessary to build confidence in the model's ability to represent the real system. Various tests can be conducted in this stage, including dimensional consistency test, extreme conditions test, sensitivity analysis, and behavior pattern test. Once a model is deemed to be credible it can be used for policy analysis.

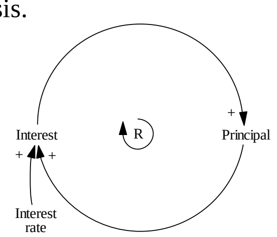

FIGURE I
REINFORCING LOOP

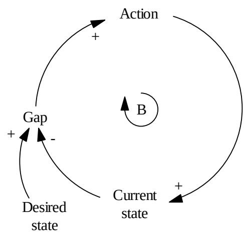

FIGURE II
BALANCING LOOP

FIGURE III
STOCK AND FLOW

III. SYSTEM DYNAMICS MODELING PROCESS

In this study, the problem of interest is relatively poor safety performance in SCCs. A causal loop diagram (CLD) that qualitatively describes the dynamics of safety motivation was then developed based on a literature review. As shown in Fig. 4, the CLD captures relationships between various subsystems (e.g., regulation, production, and safety).

Feedback loops B1, B2, R1, and R2 address both positive and negative effects of safety regulations on small construction companies' safety management competency and motivation. These four feedback loops capture the dynamics of a combination of "carrot and stick" approaches adopted by the government to help and motivate small construction companies to manage safety. The balancing loop B1 describes how government agencies (e.g., Work Safe New Zealand) provide information and guidance to help small businesses to comply safety rules, by establishing a set of safety regulations and approved codes of practice. In general, the information and guidance, together with other support services and enforcement activities (such as audits, inspections, and investigations), enhances small construction companies' competency to manage safety and therefore reduce accidents and injuries. Another balancing loop B2 captures the deterrence effects of penalty on small construction companies. Prosecutions and penalties would apply where serious non-compliance occurs. They act as a threat to deter construction companies from offending. To avoid punishment and ensure compliance, small construction companies are motivated to take "all practicable steps" to ensure the safety of employees while at work. The government may increase penalties by developing new tiered penalty regimes, in response to historical safety performance of the industry [26].

Reinforcing loops R1 and R2 illustrate the side effects of the "carrot and stick" approach. Although current New Zealand safety legislation system is performance-based, which establishes mandatory goals rather than enforces prescriptive standards, small construction companies seem to be more comfortable with detailed prescriptions. They tend to wait safety inspector to advise them what should be done in order to meet safety rules. As a result, a reactive compliance culture can be created over time, which can undermine their safety motivation by generating a loss of safety ownership [27] and a reactive prevention mode [28], as shown in the R1. Another downside of current safety regulations is that compliance involves the massive volume of paperwork (R2 Safety regulations generate paperwork). Documenting safety activities and writing safety reports is not necessarily counter-productive, as the documentation in a sense is a reflection of actual safety efforts made on site. However, paperwork can be divided into two types: that helps keep a safe site and that only seeks compliance [29]. It would be far from effective to monitor the safety level of a project if managers focus on the latter [29, 30].

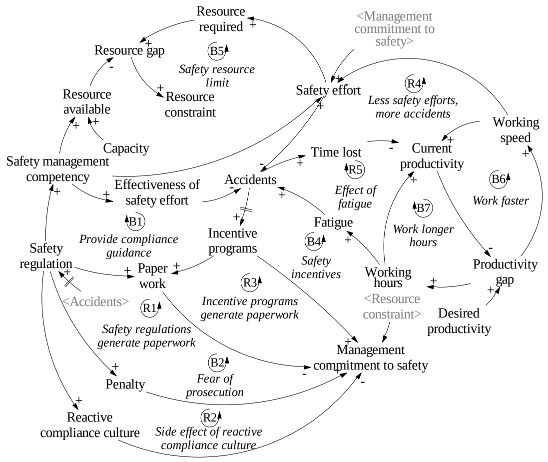

FIGURE IV.
CAUSAL LOOP DIAGRAM

Feedback loops B4 and R3 capture the dynamics of safety incentive programs designed by the government. As a significant part of the rehabilitation and compensation system, incentives programs, such as Workplace Safety Discount (WSD) were designed and implemented by Accident Compensation Corporation (ACC), with an attempt to motivate small businesses to manage safety by providing a range of discounts of ACC work cover levies [31]. As suggested in the B4, to get the discount, small construction companies are motivated to design and implement certain safety practices and meet requirements pre-set by the ACC. By doing so, the level of management commitment to safety would be improved and accidents would decrease. However, similar to safety regulations, incentive programs involve paperwork, which often cause a missing link to safety practices implemented on site. Those small companies who are oriented toward discounts often take the shortest and quickest path to get them by even buying documents from consultants.

The balancing loop B5 describes how safety resource constraint limits safety efforts. As described in the B5, there is often gap between resource available and resource required. Because of the gap, small construction companies are "forced" to reduce safety efforts (e.g., safety training) even though they are highly motivated.

Feedback loops B6, B7, R4, and R5 captures the dynamic relationships between production and safety. It is common that small construction companies place production over safety in order to improve productivity and catch up schedule delay. They mainly adopt two approaches: work faster and work longer hours. As shown in the B6, when the gap between desired and current productivity widens, working speed increases. In this situation, safety practices are ignored and unsafe behaviors are gradually accepted. Workers are "forced" to work quickly by taking shortcuts in order to satisfy their boss and complete the tasks as soon as possible. As a consequence, more unsafe behaviors result in more accidents. Similarly, working longer hours is often an approach to improve productivity, as shown in the B7. However, these two approaches carry side effects that, from a long-term perspective, worsen the productivity problem. For the "working faster" strategy, the side effect is that as emphasis is placed on productivity, safety efforts would be reduced and therefore more accidents would occur, which, in turn, would lose more labor time and thus worsen productivity (see R4). In addition, working longer hours would cause an issue of fatigue. Fatigue negatively affects workers' ability to think clearly and act appropriately. Fatigued workers are less alert and therefore are more likely to have accidents and injuries. If it remains unmanaged, a vicious circle would emerge, as shown in R2 effect of fatigue.

The causal loop diagram was then transferred into stock and flow diagram for simulation (see Appendix I).

Initial conditions of the quantitative model are defined according to typical features of small construction companies. Table 1 lists initial value and unit of each parameter in the stock and flow diagram.

The model was then validated by extreme condition testing, sensitivity analysis, dimensional consistency, and assessment of whether model structure and parameter values are consistent with reality of safety management in small construction companies and literature findings. The results for various extreme condition tests are shown in Table 2.

TABLE I
PARAMETER VALUES

Model parameter	Value	Unit
Time to increase safety competency	10	week
Time to lose safety competency	100	week
Time to change working speed	1.5	week
Time to increase productivity	4	week
Time to change working time	1.5	week
Time to decrease productivity	8	week
Management safety motivation	30	%
Safety competency	20	%
Safety effort	50	%
Resource available	50	%
Paperwork	70	%
Reactive compliance culture	20	%
Safety pressure	0	%

TABLE II
RESULTS FOR EXTREME CONDITION TESTS

Model parameter	Test	Value	Test result
Organizational ability to learn	No ability to learn	0	Safety competency drops gradually to about 16, but has almost no effect on accident rate.
Resource	No	0	Safety effort decreases

available	resource		quickly to 29. Accident rate increases quickly to 40.
Initial value for Management safety motivation	None	0	Management safety motivation approaches to trajectory when its initial value is 20.
Initial value for Safety competency	None	0	Safety competency increases from 0 to 20.

The main purpose of sensitivity analysis is to determine how "sensitive" a model is to changes in the value of the parameters of the model. A total of seventeen invariant constants were identified and tested for sensitivity. Fig. 5 and Fig. 6 present the results of sensitivity analysis conducted by Vensim, a system dynamics modeling application.

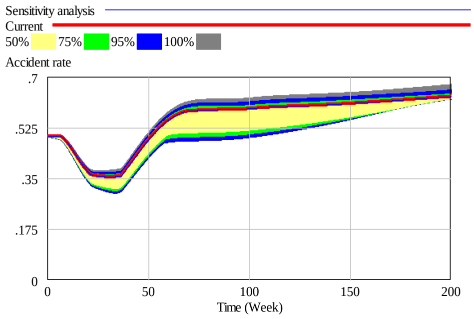

FIGURE V
ORGANIZATIONAL ABILITY TO LEARN

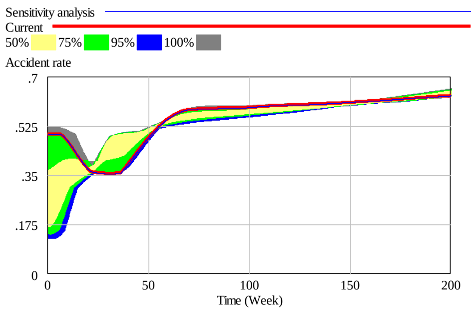

FIGURE VI
MANAGER'S SAFETY ATTITUDE

The tests have identified a number of sensitive parameters. As presented in Table 3, parameters, like "Time to increase management safety motivation", "Time to decrease management safety motivation", "Time to increase safety pressure", "Time to decrease safety pressure", and "Manager's safety attitude", were identified as highly sensitive. Thus, policy analysis can concentrate on setting these parameters which have been shown to be most significant.

TABLE III
Sensitivity of constant parameters

Constant Parameters	Sensitivity
Time to increase management safety motivation	High
Time to decrease management safety motivation	High
Time to develop reactive compliance culture	Low
Time to decrease reactive compliance culture	Low
Time to complete paperwork	Low
Time to increase in safety competency	Very low
Time to decrease in safety competency	Very low
Time to increase safety pressure	High
Time to decrease safety pressure	High
Time to change the perception of resource gap	Very low
Time to change safety effort	Low
Dilution time	Low
Manager's safety attitude	High
Time to change working time	Medium
Time to change working speed	Low
Time to increase productivity	Medium
Time to decrease productivity	Medium

A base case simulation, in which all parameters were in initial conditions, was run to show the dynamics of the model. As shown in Fig. 7, with the support provided by the government agencies, safety competency of small construction companies steadily improves. The level of management safety motivation increases quickly in initial stages, due to positive effects of incentive programs and penalty. However, it starts to drop after the 20th week because of negative effects of paperwork, reactive compliance culture, and a lack of safety resource. Due to a time lag between management safety motivation and accident, average accident rate does not increase until the 70th week. When those negative and positive effects reach a dynamic equilibrium, management safety motivation levels off.

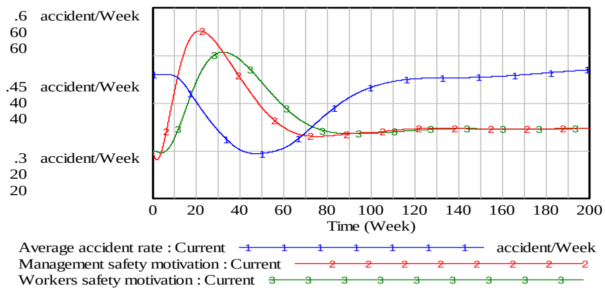

FIGURE VII
BASE RUN

In the second case, effects of safety resource on accident rate were analyzed. Three scenarios were simulated: resource available=50, 80, and 100. As shown in Fig. 8 and 9, different initial values of resource available do not alter the behavior mode of accident rate. However, it is clear that companies with more safety resource have lower accident rate. This is because of the fact that resource available influences management safety motivation and then safety efforts.

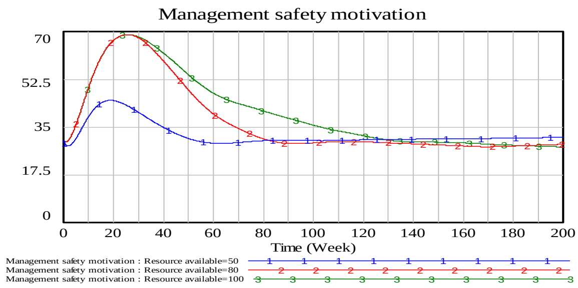

FIGURE VIII
EFFECTS OF "RESOURCE AVAILABLE" ON MANAGEMENT SAFETY MOTIVATION

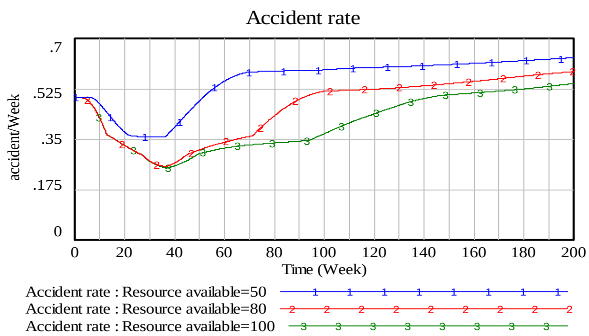

FIGURE IX
EFFECTS OF "RESOURCE AVAILABLE" ON ACCIDENT RATE

In the third case, effects of "time to increase safety pressure" on accident rate were investigated. This parameter in some extent reflects, and is determined by, a manager's safety attitude towards accidents and employees' safety. A high value of the parameter means that the manager is insensitive and unconcerned about accidents. As suggested in Fig. 10 and 11, accident rate is very sensitive to the change of "time to increase safety pressure". When managers need a relative long time to perceive safety pressure (Time to increase safety pressure=10 weeks), accident rate is higher than the other two scenarios (Time to increase safety pressure=5 and 2 weeks). From a system dynamics perspective, a longer time to increase safety pressure represents a longer delay between accidents and management safety motivation.

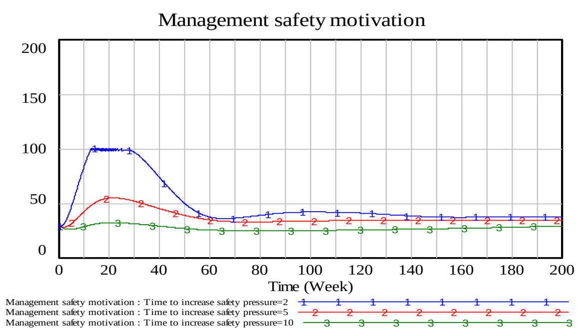

FIGURE X
EFFECTS OF "TIME TO INCREASE SAFETY PRESSURE" ON MANAGEMENT SAFETY MOTIVATION

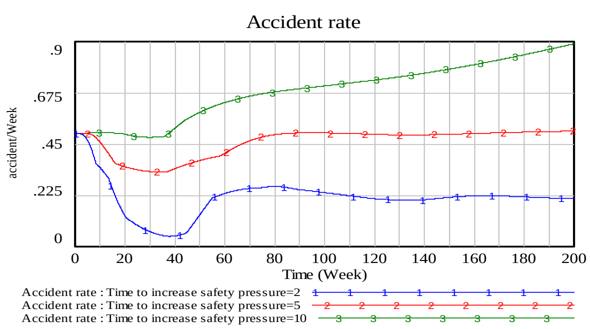

FIGURE XI
EFFECTS OF "TIME TO INCREASE SAFETY PRESSURE" ON ACCIDENT RATE

IV. CONCLUSIONS

This paper developed a system dynamics of management safety motivation of small construction companies, with an attempt to describe its dynamics by capturing complex interactions among variables in different subsystems. The simulation model illustrated the dynamic and interactive relationships among the variables in various subsystems (i.e., regulation, production and safety). A system dynamics modeling of safety management in small construction companies generates systemic insights into accident prevention strategy.

First, safety, as well as accidents, should be considered as a system problem. This conclusion rests in part on the analysis and simulation of safety management in small construction companies. It is not sufficient and effective to explain accidents as results of a low level of safety motivation. Effects of factors in other subsystems (e.g., regulation and production) need to be taken into account. Emphasis here should be placed on interrelationships among these factors, rather than individual factors.

Second, this paper adopts a dynamic view on safety problems facing small construction companies. Dynamic problems are characterized by variables that undergo significant changes over time. The simulation results suggest how key variables (i.e. workers and managers safety motivation, safety effort, safety competency, and productivity) in the model change over time. The dynamics of these variables reflect the dynamics of safety conditions of small construction companies. Third, as dynamic behavior of a system is determined by it structure, solutions that improve safety performance of small construction companies lie in the dynamic structure of the model. The policy analysis conducted in this paper suggests that increasing the capacity of small construction companies would be effective to improve safety performance. In addition, managers' safety attitude towards accident also plays a high leverage point in accident prevention strategy.

In summary, a system dynamics modeling (qualitative and quantitative) of safety management enhances an understanding of the dynamic complexity of safety problems facing small construction companies and bridges the gap between systems theory and practice in safety management in small construction companies.

VI. ACKNOWLEDGEMENT

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Appendix I: Stock and flow diagram