THE USE OF SYSTEM DYNAMICS MODELLING IN IMPROVING CONSTRUCTION SAFETY

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ABSTRACT

The construction project has a predetermined date of delivery, is subject to one or several performance goals, and consists of a number of complex activities. These characteristics make the construction industry one of the most hazardous industries, resulting in high rates of accidents. The main cause of construction accidents is viewed as the direct result of having a poor safety culture. Much attention has been paid to organizational safety culture, and to the development of tools for monitoring its health, in order to identify areas for safety improvement.

This paper aims to develop the construction safety culture (CSC) dynamic model, utilizing the system dynamics (SD) modeling, to capture the interactions among key factors of CSC over a period of time. The *CSC index*, developed through SD modeling, is used to measure the level of CSC maturity, and identify areas for safety improvement. Furthermore, dynamic simulations for two organizations are performed, and simulation results are investigated. The organizations could also perform a number of policy experiments to underline areas for safety improvement, and select the best policy that matches its situation.

KEY WORDS

Construction industry, CSC dynamic model, CSC improvement, CSC index, policy experiments.

INTRODUCTION

The construction industry is “the units mainly engaged in construction, repair, alteration, and renovation of buildings and other structures, and those engaged in providing building or construction trade services and specific installation activities” (Australian Bureau of Statistics, 1993). It comprises many organizations, and operates on international, national, and local scales, with participants ranging from large multinational organizations to single person operations. The projects may vary from simple dwellings to complex structures, and normally involve many changes, such as frequent teamwork rotations and high rates of unskilled workers (Rosenfeld et al., 2006). These characteristics make the construction industry one of the most hazardous industries resulting in high rates of accidents (Maloney, 2003). Construction accidents de-motivate workers, delay project progress, and adversely affect the overall cost, productivity, and reputation of the construction industry (Mohamed, 1999). According to Smith and Roth (1991), the main cause of construction accidents is the

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direct result of having a poor safety culture. Since poor safety culture can lead to risks to human lives, much attention has been paid, over the past few years, to organizational safety culture, especially to its definitions, dimensions, as well as to the development of tools for assessing its ‘health’, in order to identify areas for safety improvement. The establishment of a good culture of safety can undoubtedly help organizations to control and reduce their construction costs, and increase the efficiency of their operations in the long term (Fung et al., 2005).

Recently, many research studies have been undertaken in the area of *construction safety culture* (*CSC*), as well as the development of the tools to assist in measuring the CSC. Kartam et al. (2000), for example, studied problems of construction safety in Kuwait, and concluded that safety culture improvement, especially in areas such as management training and commitment in safety, was needed to prevent construction injuries and accidents. Mohamed (2003) adopted a Balanced Scorecard tool to benchmark organizational safety culture. Ho and Zeta (2004) studied safety in the Hong Kong construction industry, and established four key cultural factors (environment, behavior, organization, and person) that affect the CSC.

The above tools are an indication of how researches are rapidly progressing towards the development of a reliable and valid instrument to measure organizational safety culture. A major shortcoming with these tools, though, is the inability to appropriately capture the causal links between what the organization is doing and what it aims to achieve (called the *Enablers* and *Goals*, respectively). Another element of weakness lies in a lack of understanding about the interactions among different enablers, as well as the extent of their individual, or combined, effects on the organization’s ability to achieve safety performance improvements. There has also been little examination of the extent to which there is a consensus among workers and managers regarding the contributions of the identified enablers in determining perceptions of safety culture. In other words, organizations should realistically assess their organizational safety culture maturity level, and progress sequentially through different levels of cultural maturity. This study, thus, sets out to develop a CSC dynamic model, utilizing the system dynamics (SD) modeling technique, to investigate the interactions among the CSC enablers and *Goals*, and to predict the influence of each enabler on safety goals, over a period of time. The *CSC index*, developed through the SD simulation, is used to measure the current CSC maturity level, and plan for CSC improvement to progress through to higher maturity levels.

SYSTEM DYNAMICS MODELING

The system dynamics (SD) modeling was first introduced as a method for modeling and analyzing the behavior of complex social systems, particularly in an industrial context. It has been used to examine various social, economic, and environmental systems, where a holistic view is important, and feedback loops are critical to the understanding of the interrelationships. Simonovic (2005) stated that a SD simulation approach relies on an understanding of complex interrelationships existing among different elements within a system. This understanding is achieved by developing a model that can simulate and quantify the behavior of the system over time. Such simulations are considered essential in understanding the dynamics of the system. However, it is difficult to evaluate a SD, as there are no performance criteria for such an evaluation (Barnes et al., 2005). Nevertheless, some of its strengths and limitations are stated. The strengths of SD applications are that: it looks at the policies as well as the processes; it provokes serious systems thinking; and it includes high (qualitative) level, as well as low (quantitative) level, analysis. Some limitations of SD applications are that: it may be difficult to apply at detailed levels; it is difficult to set the boundary of the system; and it has a problem with the time horizon. Despite these limitations, the SD methodology provides a good basis from which to make decisions. It allows for the interrelationships among important variables, all of which affect the problem, thus providing a better understanding of the problems, and the ways in which it can be solved.

In the construction domain, many researchers have reported SD modeling applications. Love et al. (2000), for example, developed a SD model to capture the interrelationships among factors that contribute to design errors and reworks in construction projects. Tang and Ogunlana (2003a) used SD modeling to gain insights into the interactions between a country's construction market and the organization's financial, technical, and managerial capabilities. They also employed the SD methodology to provide a careful and holistic evaluation of the improvement policies to enhance organizational performance (Tang and Ogunlana, 2003b).

In this study, the SD modeling is used to capture the interactions and causal relationships among the enablers of CSC, over a period of time. The reasons for its use are that: 1) The SD modeling can be used to deal with the dynamic changes, 2) SD modeling can be used to capture the feedback processes (i.e. to investigate the interactions among the CSC enablers, and the feedback of *Goals* on the enablers), 3) SD modeling permits the use of soft data in the modeling, and 4) SD modeling can test alternative strategies to improve the CSC without actually having to implement them; this saves money by eliminating costs that may occur from not implementing the best strategy.

THE PROPOSED CSC MODEL

The CSC model is hypothesized based on the logical assumption that by improving how the organization operates, there will be an inevitable improvement in the results. This same assumption underlies the most commonly applied model for TQM known as the EFQM (European Foundation for Quality Management) Excellence model. Empirical evidence suggests that the application of holistic management models, such as the EFQM Excellence model, has a positive effect on organizational performance (Kristensen and Juhl, 1999). The proposed CSC model (as shown in Figure 1) consists of six constructs, five 'enablers' and a single set of *Goals*. The enablers represent how the organization operates, and the *Goals* construct concentrates on achieving predetermined organizational goals. The interactions and causal links of the six constructs are examined using the statistical technique of structural equation modelling (Chinda and Mohamed, 2008). This is carried out to gain an insight into the associations among the different constructs of the CSC. In addition to the enablers and *Goals*, the criterion weights are also an important part of the model. According to EFQM (2000), a total of 1,000 points of the proposed model is evenly split (500/500) between the enablers and *Goals*. The 500 points allocated to the enablers are distributed as follows: 100 points to *Leadership (Lds)*, 80 points to *Policy and Strategy (Pol)*, 90 points to *People (Ppl)*, 90 points to *Partnerships and Resources (Prs)*, and 140 points to *Processes (Pro)*. The *Goals* construct, on the other hand, contains 500 points. These criterion weights are used to develop a so-called *CSC index*, for assessing the CSC maturity level in the organization.

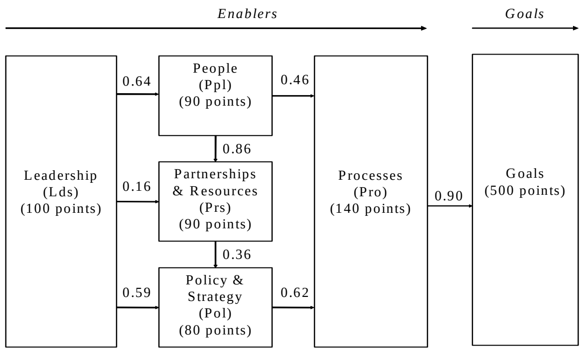

Figure 1: The Proposed CSC Model

It is important that an organization be able to assess its current maturity level, as the type of improvement method, needed to support safety culture development, differs as safety culture matures (Lardner et al., 2001). Consequently, a safety improvement method may fail if it is not matched to the maturity of the organization's existing safety culture. According to Lardner et al. (2001), the safety culture maturity model consists of five levels of maturity (emerging, managing, involving, cooperating, and continually improving). Deciding which level is most appropriate needs to be based on the average level achieved by the organization or site being evaluated. It is suggested that organizations progress sequentially through the five levels, by building on the strengths, and removing the weaknesses of the previous level. To be able to assess the level of CSC maturity, each maturity level needs a score-range (zero to 1,000 points). According to score-range diversities, this research utilizes the score-range of 200 points for each maturity level. These score ranges are used, together with the *CSC index*, to identify the CSC maturity level in the organization.

THE CSC DYNAMIC MODEL

The CSC dynamic model (as shown in Figure 2) is developed based on the proposed CSC model to capture the interactions among the five enablers and *Goals*, where the *CSC index* represents the sum of the *Enablers* and the *Goals* scores. To illustrate, the *Lds* dynamic model provides a simple representation of stock (leadership) and flow (rlds = leadership rate) diagram. In this model the increase of 'rlds' depends on the value of leadership (used_lds), leadership rate fraction (rldsf), gap of goals (ggoals), gap of leadership (glds), and the percentage more effort provided to improve the leadership score (plds), as shown in the equation below.

rlds = ((used_lds + ggoals)*rldsf) + (glds*plds)

When 'ggoals' is large (in other words the score of goals is low compared to the 500 target score), leadership must try to reduce this gap by, for example, committing more on safety and being a role model in behaving safely. The increased 'rlds' rises 'leadership' stock which in turn increases 'used_lds' value. This value is then transferred to the next models namely, the *Ppl*, *Prs* and *Pol* dynamic models, as seen from the arrows pointing from 'used_lds' to 'rppl', 'rprs' and 'rpol', respectively. In the *Ppl* dynamic model, the increased or decreased ‘used_lds’ value will have an effect on people rate (rppl). This, in turn, will affect the value of ‘used people’ (used_ppl). The same idea is applied to the *Prs* and *Pol* dynamic models. The simulations iterate as cycles, from the *Lds* to *Goals* dynamic models, in which in each cycle, the *Enablers* score and the *CSC index* are calculated.

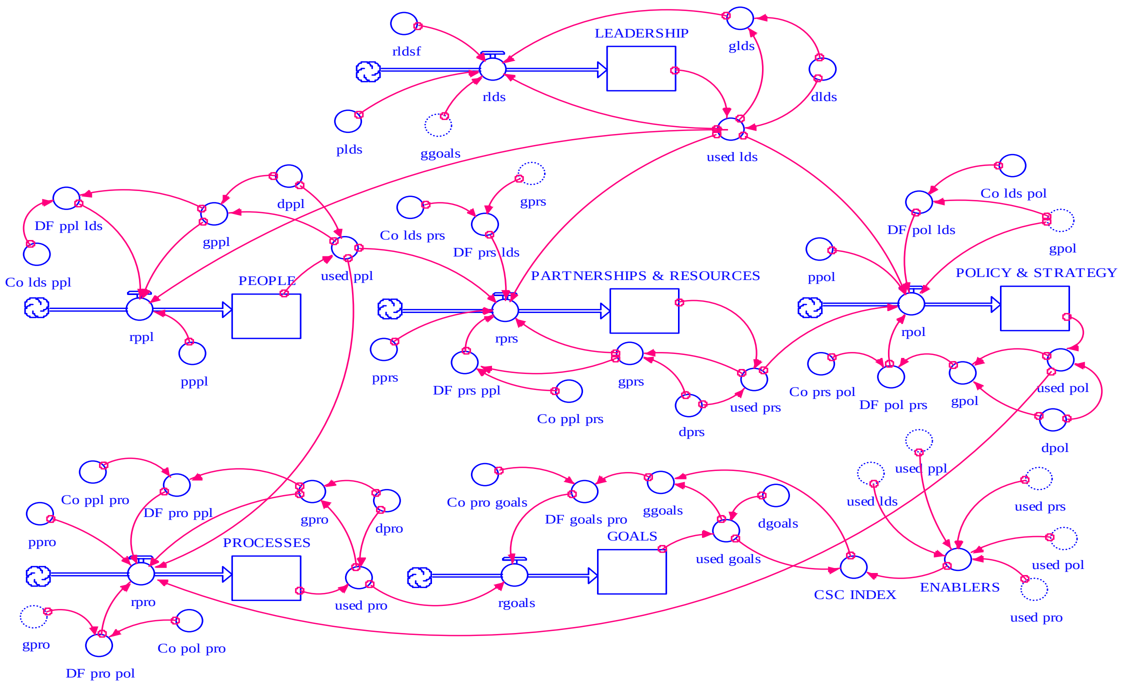

Figure 2: The CSC Dynamic Model

SIMULATION RESULTS

BASE RUN RESULTS OF ORGANIZATION ‘A’

The data of two organizations are used in the SD simulations. The initial values of the six constructs derive from the data collected from the questionnaire survey, and are transformed to the values proportioned to their limited points (for example, the *Lds* score of three out of five is converted to 60 out of a maximum of 100 points).

In organization ‘A’, the six values are 20, 43.2, 18, 19.2, 37.3, and 129 points for *Lds*, *Ppl*, *Prs*, *Pol*, *Pro* and *Goals*, respectively, leading to the initial value of the CSC index of 266.7 points (the second level of CSC maturity). The SD simulations are performed, and the results are illustrated in Tables 1 and 2, and Figure 3, respectively.

Table 1: Simulation Results of the Five Enablers of Organization ‘A’

Year	Lds		Pol		Ppl		Prs		Pro	
	Score	Gap*	Score	Gap	Score	Gap	Score	Gap	Score	Gap
Initial	20.00	80.00	19.20	60.80	43.20	46.80	18.00	72.00	37.30	102.7
1	26.73	73.27	32.33	47.67	49.62	40.38	44.20	45.80	69.32	70.68
2	36.89	63.11	47.48	32.52	56.87	33.13	63.08	26.92	97.43	42.57
3	46.23	53.77	60.53	19.47	64.56	25.44	75.59	14.41	117.83	22.17
4	55.50	44.5	69.59	10.41	71.80	18.2	82.99	7.01	129.83	10.17
5	**64.95**	35.05	**74.87**	5.13	**77.70**	12.3	**86.87**	3.13	**135.76**	4.24

Note: Bold numbers refer to the time unit where the organization reaches its fifth level of CSC maturity. (*)Gap = the difference between the maximum and the achieved scores

Table 2: Simulation Results of the Enablers, Goals, and CSC Index of Organization 'A'

Year	Score Enablers	Score Goals	CSC Index	CSC Maturity Level
Initial	137.70	129.00	266.70	2nd
1	222.21	155.75	377.96	2nd
2	301.76	226.78	528.54	3rd
3	364.73	300.88	665.61	4th
4	409.70	372.86	782.56	4th
5	**440.16**	**444.63**	**884.79**	**5th**

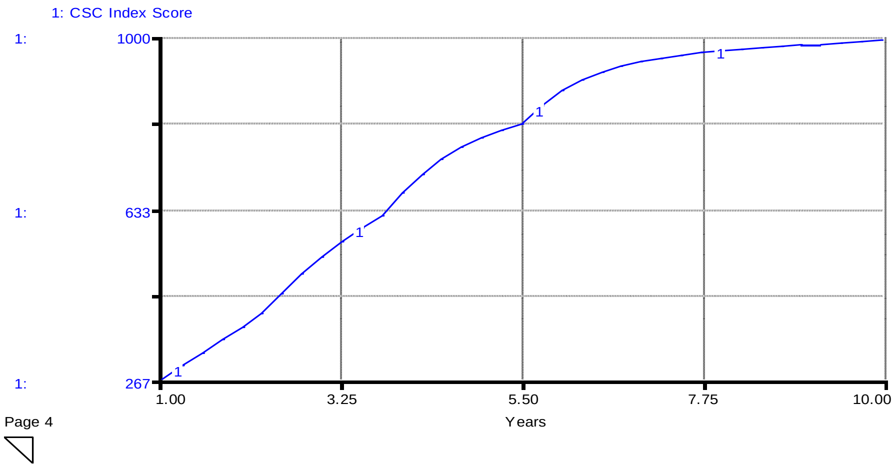

Figure 3: Graphical Results of the CSC Index of Organization 'A' over Time

The results show that it takes five years for the organization to progress from the second to the fifth maturity levels. To demonstrate, it takes two years for the organization to reach the third maturity level. The organization then advances through to the fourth level in one year, and reaches the fifth level of maturity at the end of year five. When organization 'A' reaches the fifth CSC maturity level, the scores of *Prs*, *Pro*, and *Pol* are close to their maximum scores, while the gaps of the *Lds* and *Ppl* values are relatively large. Thus, to plan for safety improvement and achieve the fifth maturity level in a shorter time frame, the organization should pay more attention to improving the *Lds* and *Ppl* enablers.

BASE RUN RESULTS OF ORGANIZATION 'B'

The initial values of organization 'B' are 85, 43.2, 40.5, 35.2, 56.0, and 200 points for *Lds, Ppl, Prs, Pol, Pro,* and *Goals*, respectively, leading to an initial CSC index of 459.9 points (the third CSC maturity level). The initial value of *Lds* is relatively high (85 out of 100 points), demonstrating a strong management commitment to safety. The simulation results for this organization are presented in Tables 3 and 4, and Figure 4, respectively. It takes three years for organization 'B' to progress from the third to the fifth maturity levels. The scores of the five enablers at the end of year three indicate that organization 'B' should place more attention on the *Pro* and *Ppl* enablers, as they produce the largest score-gaps compared with the other three enablers.

Table 3: Simulation Results of the Five Enablers of Organization 'B'

Year	Lds		Pol		Ppl		Prs		Pro	
	Score	Gap*	Score	Gap	Score	Gap	Score	Gap	Score	Gap
Initial	85.00	15.00	35.20	44.80	43.20	46.80	40.50	49.50	56.00	84.00
1	98.72	1.28	59.56	20.44	64.95	25.05	63.96	26.04	91.96	48.04
2	100.00	0.00	72.05	7.95	77.50	12.50	78.85	11.15	118.47	21.53
3	**100.00**	0.00	**77.08**	2.92	**83.77**	6.23	**85.71**	4.29	**131.50**	8.50

Table 4: Simulation Results of the Enablers, Goals, and CSC Index of Organization 'B'

Year	Score			CSC Maturity Level
	Enablers	Goals	CSC Index	
Initial	259.90	200.00	459.90	3rd
1	379.14	249.42	628.56	4th
2	446.86	347.65	794.51	4th
3	**478.06**	**449.15**	**927.21**	**5th**

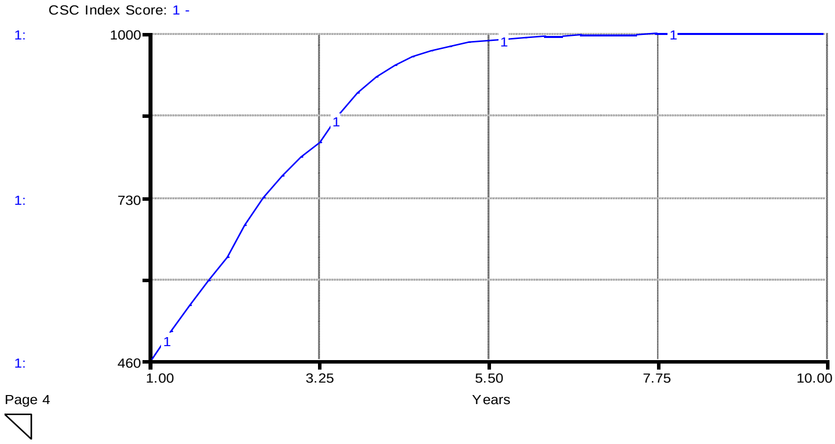

Figure 4: Graphical Results of the CSC Index of Organization 'B' over Time

POLICY EXPERIMENTS

Policy Experiments of Organization 'A'

The gaps of the *Lds* and *Ppl* values are relatively large, when compared with those of the other three enablers (see Table 1). With this in mind, planning for safety improvement should be performed in the *Lds* and *Ppl* areas, if organization 'A' expects to achieve a higher CSC index value, and reach the fifth maturity level in a shorter time period. Simulations, with different policy scenarios, focusing on improving these two enablers may be conducted to achieve the most effective policy.

In reaction to the large gap in the *Lds* score, the organization must allocate more effort to improving the *Lds* value by, for example, setting the percentage of more effort provided to improve the *Lds* score (plds, see Figure 2) to 0.1, representing the 10% more effort (in the base run, the organization considers all five enablers as having equal significance in improving the CSC index, so the 'plds' is set as zero). The dynamic model is, then, run, and the simulation results predict that the organization reaches the CSC maturity one year earlier (see Tables 5 and 6) i.e. within four years; one year faster than the initial run results.

Table 5: Simulation Results of the Five Enablers of Organization 'A' with 'Plds'=0.1

Year	Lds		Pol		Ppl		Prs		Pro	
	Score	Gap*	Score	Gap	Score	Gap	Score	Gap	Score	Gap
Initial	20.00	80.00	19.20	60.80	43.20	46.80	18.00	72.00	37.30	102.70
1	34.40	65.60	33.22	46.78	50.41	39.59	44.51	45.49	69.45	70.55
2	51.33	48.67	50.25	29.75	59.72	30.28	64.16	25.84	98.33	41.67
3	67.81	32.19	64.23	15.77	69.35	20.65	77.08	12.92	119.21	20.79
4	**82.58**	17.42	**72.87**	7.13	**77.44**	12.56	**84.31**	5.69	**131.00**	9.00

Table 6: Simulation Results of the Enablers, Goals, and CSC Index of Organization 'A' with 'Plds'=0.1

Year	Score			CSC Maturity Level
	Enablers	Goals	CSC Index	
Initial	137.70	129.00	266.70	2nd
1	232.00	155.76	387.76	2nd
2	323.78	227.08	550.87	3rd
3	397.70	319.96	717.65	4th
4	**448.19**	**407.42**	**855.61**	**5th**

Lds still has the least score (the gap of the *Lds* score is the largest), when compared with the other four enablers. This outcome may indicate that more effort is still needed to further improve the *Lds* value. The organization may further experiment with, for example, 20% more effort (instead of the 10% given in the last simulation) to improving the *Lds* enabler. The model is simulated, and the results are shown in Tables 7 and 8.

Table 7: Simulation Results of the Five Enablers of Organization 'A' with 'Plds'=0.2

Year	Lds		Pol		Ppl		Prs		Pro	
	Score	Gap*	Score	Gap	Score	Gap	Score	Gap	Score	Gap
Initial	20.00	80.00	19.20	60.80	43.20	46.80	18.00	72.00	37.30	102.70
1	41.50	58.50	34.08	45.92	51.16	38.84	44.80	45.20	69.58	70.42
2	63.29	36.71	52.58	27.42	62.10	27.90	65.09	24.91	99.13	40.87
3	83.52	16.48	66.88	13.12	72.79	17.21	78.23	11.77	120.30	19.70
4	**99.71**	0.29	**74.76**	5.24	**80.71**	9.29	**85.16**	4.84	**131.79**	8.21

Table 8: Simulation Results of the Enablers, Goals, and CSC Index of Organization 'A' with 'Plds'=0.2

Year	Score			CSC Maturity Level
	Enablers	Goals	CSC Index	
Initial	137.70	129.00	266.70	2nd
1	241.12	155.76	396.88	2nd
2	342.19	227.36	569.55	3rd
3	421.73	333.83	755.55	4th
4	**472.13**	**431.83**	**903.96**	**5th**

By setting the 'plds' = 0.2, the organization reaches the fifth CSC maturity level in four years, which is the same time frame of when the 'plds' = 0.1. However, the scores of the five enablers, as well as the CSC index, at the end of year four, appear to be higher than those obtained when the 'plds' = 0.1. Consequently, the organization needs further experiments with different 'extra' efforts for improving the scores of the five enablers to achieve a higher *Goals* score and reach the CSC maturity as planned.

POLICY EXPERIMENTS OF ORGANIZATION 'B'

The base run results of organization 'B' illustrate that it takes three years for the organization to progress from the second to the fifth levels of CSC maturity. For organization 'B' to achieve maturity earlier (less than three years), a number of sensitivity analyses, with, say, 10% extra effort being given to improve each enabler (the 'plds', 'pppl', 'pprs', 'ppol', and 'ppro') need to be undertaken. The analyses help to identify which enabler has the potential to increase the CSC index so that the organization reaches the CSC maturity level earlier. The sensitivity analysis results, illustrated in Table 9, demonstrate that, by giving the 10% more effort to enhance the score of *Pro* ('ppro' = 0.1), organization 'B' achieves its maturity one year earlier, i.e. within two years. The results of the other four enablers, however, show no advancement in the organization achieving the fifth CSC maturity level earlier. Thus, to improve safety performance and achieve the fifth CSC maturity level, in a shorter time period, organization 'B' should focus on enhancing the improvement of the *Pro* enabler, as it facilitates a faster CSC maturity achievement.

Table 9: The CSC Index of Organization 'B' when More of Effort is Given to Enhance each Enabler

Year	CSC Index					
	Base Run	**Plds = 0.1**	**Ppol = 0.1**	**Pppl = 0.1**	**Pprs = 0.1**	**Ppro = 0.1**
Initial	459.90	459.90	459.90	459.90	459.90	459.90
1	628.56	629.71	631.44	632.15	631.63	635.25
2	794.51	794.69	797.20	798.49	797.13	**802.76**
3	**927.21**	**927.31**	**928.79**	**930.02**	**928.67**	942.50

CONCLUSION

Throughout the world, the construction industry has had a poor safety record, and is disproportionately more dangerous when compared to other industries. The major cause of construction accidents is attributed to unsafe behaviors and work practices, which are viewed as the direct result of having a poor safety culture. Better understanding of safety culture and causal relationships between its key elements is a must for construction organizations to strategically allocate their safety resources.

In this paper, the CSC dynamic model is formulated to capture the interactions and causal relationships among the six constructs (five enablers and *Goals*) of the model, over a period of time. The CSC index, developed through the dynamic model, represents the sum of the five enablers and *Goals*' values at a point in time, and is used together with the five levels of CSC maturity to indicate the current CSC maturity level. Policy analyses are performed with two organizations ('A' and 'B'), currently in the second and third levels of CSC maturity, respectively. A number of safety policies are tested to identify the most effective policy each organization could apply to enhance its CSC index, and progress through to the fifth CSC maturity level.

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