Understanding and Improving System Safety through System Dynamics Modelling – Systematic Literature Review

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Abstract. System Dynamics (SD) has been widely used in modelling across a range of applications that range from socio-economic to engineering systems, but its potential has not yet been fully realised as a tool for understanding system safety and supporting relevant strategic decision making. We conducted a literature review of SD applications in safety-critical environments, employing a safety taxonomy framework. The result of our literature review provides an overview of SD modelling application in safety-critical environments, highlighting the existing gap and generating future research questions in this area.

Keywords. system dynamics, literature review, simulation modelling, safety.

1. Introduction

The SD method has been used to obtain in-depth understanding of the system and to answer “what if” questions, investigating the effect of system changes over time. Whilst SD modelling has gained popularity as a tool in a variety of industries such as engineering, economics, defence, ecology and business (Homer & Hirsch, 2006a), its potential has not yet been fully realised as a tool for understanding trade-offs between safety and efficiency and making strategic decisions in safety-critical industries. There are a considerable number of SD applications on safety (e.g. patient safety, traffic safety, nuclear safety, etc.) in various fields but no comprehensive systematic review of the use of SD modelling in safety-critical domains has been published. The overall aim of our study is to evaluate the extent, quality and value of system dynamics applications in safety-critical domains. To this end, this paper focuses on how SD modelling has been used in safety-critical environments as described in the literature.

2. Methods

2.1 Literature Search

Systematic methods were employed to gather and evaluate relevant papers for this literature review. A range of databases were searched for published articles up to July 2015 on system dynamics and safety. The databases include PubMed, Web of Science, Science Direct and Google Scholar databases. The grey literature was also searched using Google search with key terms mentioned below. . Papers eligible for inclusion were those that described applications of system dynamics modelling to understand/improve system safety. Specific key terms that were searched included 'system dynamics', 'safety', 'accident', 'errors'. Parallel searches, using the same key terms, were conducted on the Internet to uncover any unpublished studies on these topics. The reference lists of each article were reviewed to identify additional resources. Articles were selected on the basis of their thematic and content relevance to the inquiry. Thirty-seven papers were identified that reported findings that applied SD modelling in safety, none of them from grey literature.

2.2 Analysis - Safety Taxonomy

We adopted the combination of the Human Factors Analysis and Classification System (HFACS) framework and Rasmussen's risk management framework (Rasmussen, 1997) to identify and classify the SD applications in the selected articles. The HFACS comes equipped with its own taxonomy to classify and analyse human error and accident causations, but lacks a crucial tier that is equivalent to the government tier in Rasmussen's six-levels of risk management framework. A new tier was introduced therefore changing the original HFACS framework into an extended HFACS framework with an addition of a new tier called External Factors as shown in the first row of Table 1. This encompasses regulatory, social, political, environmental, and economic influences.

3 Results

The results of the literature search are presented in Table 1 which shows the 37 papers we identified classified according to the extended HFACS framework. The 37 papers were concentrated in the fields of aviation, construction, disaster-prevention, industrial systems, drugs and terrorism, government, healthcare, military, nuclear and traffic. Healthcare topped the list with a total of 11 papers that applied SD to improve a safety-critical aspect. Qualitative SD is based on creating casual loop diagrams and using these to explore and analyse the system. Quantitative SD is based on quantitative computer simulation modelling using purpose built software.

In terms of which modelling aspect of SD was used, studies applying only qualitative SD (casual-loop diagrams) were 11, whilst those applying quantitative SD (stock-and-flow diagrams) were 14. Lastly, the total paper applying both casual-loop and stock-and-flow diagrams numbered 12.

Authors, for instance, have improved modelling system safety problems through the application of qualitative and quantitative SD. Amongst them are enhancing healthcare safety, through estimating potential outcomes, analysing reasons other than cost on why systems safety is failing, to discussing bottlenecks in critical services. Authors have also improved safety through calling for greater decision-making by basing it on system analysis, analysing past behavioural events in modelling structure to plan effective safety policies as well as looking at a holistic approach to analyse beyond human error in accidents. These examples provide a clear indication of how, through the effective application of SD, safety can be improved in safety-critical industries.

In Table 1 the thematic content of each paper is classified according to its primary foci (highlighted in dark grey) and its secondary foci (highlighted in light grey). Primary foci are identified as the strong themes of the paper, whilst secondary foci identified as visible, but not central themes in the papers. The literature review on existing SD applications to system safety indicated that most of the literature concentrated on improving safety in the higher tiers of the hierarchy whilst a few studies has been dedicated on the operator end or the lower tiers.

Table 1: Matrix Grid of SD Applications

Primary (P)
Secondary (S)

Papers	External Factors		Organisational Influences			Unsafe Supervisions				Precondition for Unsafe Acts							Unsafe Acts				
										Environmental Factors		Condition of Operators			Personnel Factors		Human Errors			Human Violations	
	Regulatory	Others	Resource Management	Organisational Climate	Organisational Process	Inadequate Supervision	Planned Inappropriate Operations	Failure to Correct Problem	Supervisory Violations	Physical Factors	Technical Factors	Adverse mental State	Adverse Physiological State	Physical/Mental Limitation	Crew Resource	Personal Readiness	Skill-Based Errors	Perceptual Errors	Decision Errors	Routine Violations	Exceptional Errors
Anderson & Anderson, 1994			P		S																
Bouloiz, H. et al., 2013				P																	
Carhart, N.J., 2009												S			P						
Cooke, D.L., 2003			S			P	S	S	S												
Cooke, D.L. & Rohleder, T.R., 2006				P				P													
Ellis, B.Y.R.E., 2004		P																			
Goh, Y.M., Love, P.E.D., et al., 2012a				P	S																
Goh, Y.M., Love, P.E.D., et al., 2012b								S	P									P			
Goh, Y.M., Love, P.E.D., et al., 2012c				P	S																
Guo, S., Roudsari, A. & Garcez, A., 2013												P		S			P				
Han, S. et al., 2014			S											P	P						
Homer, J.B., 1984						S						P									
Jiang, Z. et al., 2015				S					S								P			P	
Kontogiannis, T., 2011																	P	P	P		
Lane, D.C., Monefeldt, C. & Rosenhead, J. V, 2000	P	S	S		S																
Lattimer, V. et al., 2004		P			S																
Leveson, Couturier & Thomas, 2012	P		S																		
McDonnell, G., 2005				S	S				P		S	P					P	P	P		
Mehmood, A., Saccomanno, F. & Hellinga, B., 2003											P	P									
Min, P. & Hong, C., 2011					S		P								S						
Minami, N. a. & Madnick, S., 2009						P	P	S	P		S				S						
Mohamed, S. & Chinda, T., 2011				P								P		S							
Morris, A., Ross, W. & Ulieru, M., 2010																					
Oliva, R., 2001																					
Rudolph, J.W. & Repenning, N.P., 2002				P	P	S															
Salge, M. & Milling, P.M., 2006						P															
Shin, M. et al., 2014																					
Simonovic, S.P. & Ahmad, S., 2005						P															
Tang, Z., 2007																					
Taylor, K. & Dangerfield, B., 2004				P	P																
Topolšek, D. & Lipičnik, M., 2009				P	P																
Ulrey, M. & Shakarian, A., 2008				S	S																
Wang, J.Y.H. et al., 2013				S																	
Wei, Z. et al., 2012											S				P		P	P	P	P	
Wu, Q. & Xie, K., 2012				S																	
Xian-gong, L., Xue-feng, S. & Xian-fei, M., 2009				P		S															
Xiao-yan, W.X.W. & Jian-hua, Z.J.Z., 2010			S		S		P														

4 Conclusion

System dynamics has the potential to significantly improve our capabilities and understanding in areas not well addressed by traditional safety approaches. It presents organisations and management as a tool for discerning the dynamic world of today, and offers insights to the potential trajectories they might encounter once faced with critical decisions that will affect safety. It allows every manager to see the wider scheme of things and help eliminate subjectivity that sometimes distorts vision. The ability of SD to demystify complex problems provides a basis for understanding the current state of the system and for identifying safety improvements.

The output indicates that the majority of implemented SD applications in all sectors are primarily focused to improve the safety of external, organisational and management tiers, not so much in the workplace environment and the operator tiers. As a result, there is a gap in the literature where applications of SD are grossly underrepresented in the sharp-end of safety. A future research question would be the utility and feasibility of applying SD to better understand, improve and aid safety amongst operators in the work environment. As evidenced in literature on safety, SD has the potential to contribute to safety in safety-critical domains although it is heavily underutilised.

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