A system dynamics approach to risks description in megaprojects development

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Technical and research paper

THE INHERENT RISKS AND THEIR INTERACTIVE IMPACTS IN MEGAPROJECT DEVELOPMENT HAVE BEEN FOUND IN NUMEROUS CASES ACROSS THE WORLD. Although risk management standards have been recommended for the best practice, there is still a lack of systematic approaches to describing the interaction among social, technical, economic, environmental and political (STEEP) risks with regard to all complex and dynamic conditions of megaproject construction for better understanding and effective management of the management mechanism in terms of the nature risks, including their dynamic interactions and impacts in megaproject development.

Purpose – Present a model to describe STEEP risks and their interactions in megaproject development.

Design/methodology/approach – A case study methodology is adopted. Following comprehensive literature review, qualitative data were gathered from case studies through interview conducted on Tram Network Project in Edinburgh. Casual loops of typical evolution of key indicators of risks were then developed and a hypothesised model of social and environmental (SE) risks was derived using system dynamics (SD) modelling technique. The model was then set up in accordance with British Standards on risk management in order to provide a generic tool for risk management in megaproject development.

Findings – The study reveals that cost and time overruns at the developmental stage of the case project are caused mainly by the ineffectiveness of traditional risks assessment techniques used in assessing risks on timely basis and accurate information from the early stages of the project. Evidences collected are used to explain the nature of STEEP risks in particular, the SE risks in the past stages of project development. Further research is also discussed for applying SD methodology in risk management in megaproject development.

Keywords

Megaproject, Risks, System dynamics, Tram project

INTRODUCTION

Risks in megaprojects construction are usually complex and uncertain. They are often referred to as the presence of potential or actual treats or opportunities that influence the objectives of a project during construction, commissioning, or at time of use (Gray, 2006). Despite the coming of age of risk management as a profession, Baker et al., (1998) established that "there is no global (project risk management) industrial standard" or procedures that exist for what constitutes a risk assessment. This implies that, there is wide range of risk management standards been discussed in literature and within the domain of project management. Some of these standards include the BS 31100:2008; BS ISO 31000:2009; BS EN 31010:2010; BS 6079-3:2000 and BS IEC 62198:2001 and the risk management standards published jointly by the Association of Insurance and Risk Managers (AIRMIC), the National Forum of Risk Management in the Public Sector (ALARM), the (AIRMIC et al, 2002) and CIRIA guide to the systematic risk management for construction (Godfrey, 1996). However, these risks management standards put forward to guide for the best practice for such a complex system like megaproject construction have not been critical enough in managing or mitigating risks from the external project environment. The conventional Standards still lack systematic approaches to describe all the interactions among the social, technical, economic, environmental and political (STEEP) risks with regard to all complex and dynamic conditions through megaproject construction that can be disastrous and can cause chronic project failure during construction.

Aim and objectives

Based on the above consideration, this paper uses System Dynamics (SD) modelling for social and environmental (SE) risk management during megaprojects development. This will be achieved through the following objectives:

- Develop SD risk assessment model to support the over 30 risk assessment techniques in the British Standards of risk management: BS 31100:2008; BS ISO 31000:2009; and BS EN 31010:2010.
- Demonstrate the effectiveness of the new SD model using an experimental case study

The significant contribution of this paper include a set of risk assessment tools for macro external project risks and an SD model designed for SE risks impact on megaproject development. It is expected that the constructed SD models will serve as promising strategic decision tools to megaproject developers for experiment during policies making and to implementing them to real situations.

Literature review

The literature review focuses on the two main areas of endeavour: (a) STEEP Risks in megaproject development (b) cost and time overruns in megaprojects construction. These two areas are selected because of their documented history in impacting upon mega construction and engineering projects:

STEEP risks in megaproject development

Risks in developmental phases of megaprojects take place within a complex web of numerous social, technological, economic, environmental and political (STEEP) environments of all types in global dimensions (Chen et al., 2009 and 2011). As a result, such large projects become: (1) extremely complex, consisting of multiple interdependent components, (2) highly dynamic, (3) involve multiple feedback process, (4) have nonlinear relationships and (5) require both "hard" and "soft" data (Sterman, 1992). Brief definitions of each of the STEEP risks are as follows:

- Social Risks: These include national and local-level factors that contribute to social (in) stability (such as levels of governance, security and population size) as well as project specific issues (the nature of the project approval process, the outcomes of similar projects previously conducted in the area, bad sub-contractor qualification, communication and low labour productivity, inexperience project manager, confusion of personnel management etc.)
- Technological risks: These risks are mainly treats that prevent the operations of the contracting companies to develop, deliver, and/or manage its services, and to support operations.
- Economic risks: Risks to constructing the Tramline projects as a result of the adjustments of national economic policy, inflation, fluctuate of price, interest rate and exchange rate due to the relative long period of delivery of such projects.
- Environmental risks: These are natural risks such as unfavourable climatic conditions (continuous rainfall, snow, temperature, wind), force majeure (thunder and lightning, earthquake, flood, hurricane, etc.) that have tremendous influence on the project and the bad environmental conditions (pollution, traffic, etc.) of construction activities on the physical environment.
- Political risks: Tram network projects, mostly belonging to a state (country) or the government, are easily influenced by the adjustment of state laws, regulations, and government policy.

Together, these STEEP risks (Figure 1) interact with one another to influence relationships and to generate risk landscapes of unprecedented complexities.

A further increase of such interactions with one another can produce system disturbances with severe consequences and would in turn generate collateral effects via spreading and cascading failures within project interrelated subsystems (Boateng et al., 2012). The results will then be crippling losses of public invested funds and valuable time that were previously thought to be uncorrelated and unforeseeable (Kytle and Ruggie, 2005).

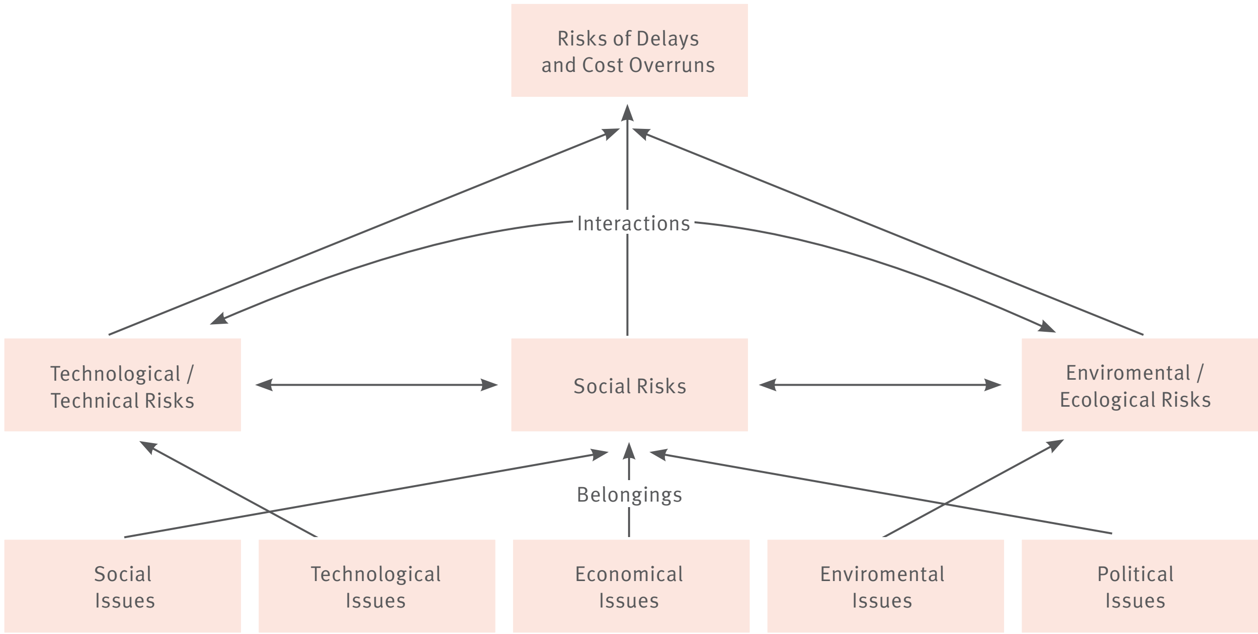


Figure 1 The effects of Interactions and belongingness of STEEP factors in megaproject dev.

Cost and time overruns in megaprojects construction

Evidence suggests that such megaprojects are usually money pits where funds are swallowed up without delivering sufficient returns. This is due to unbalanced subjective beliefs and information in assessing risks and uncertainties, and taking corrective actions to control and manage the identified risks. For example, in Poole (2004), the transportation infrastructure industry has been revealed to have a major credibility problem. It has a bad track record on megaproject development. The project costs are often grossly underestimated, and traffic, often overestimated. These problems are well documented in literature for many recent rail projects across the globe.

A study was carried out by Danish academic Bent Flyvbjerg and colleagues on 258 highway and rail projects (USD90 billion worth) in 20 countries in a book called Megaprojects and Risk (Cambridge University Press, 2003). The study revealed that transportation infrastructure projects do not perform according to budgets as estimated. According to the study, the vast majority (90%) suffered cost overruns, with the average rail project costing 45% more than projected, and the average highway project 20% more. Traffic forecasts were also far from accurate, with rail projects generating an average of 39% less traffic than forecasted (though highway projects averaged a 9% underestimate of traffic). Based on a continuous research, Bent Flyvbjerg emphasized that cost overrun has not decreased over the past 70 years and furthermore seems to be a global phenomenon.

Further high profile highway projects, are Boston's Central Artery/Tunnel, the "Big Dig" and Virginia's Springfield Interchange. These projects have made practitioners in the construction industry, and public taxpayers acutely aware of the problems of project delay and cost overruns. For example, the Big Dig was estimated at a cost of US$ 2.6 billion but was completed at a cost of US$ 14.6 billion. Additionally completion was delayed from 2002 to 2005. This indicates that construction cost estimating on major infrastructure projects has not increased in accuracy over the past 70 years. The underestimation of cost today is in the same order of magnitude that it was then (Flyvbjerg, 2006b, 2007). According to Flyvbjerg et al. (2003), there is need for new ideas and techniques to be developed to improve this area where no leaning seems to have taken place. Flyvbjerg however proposes reference class forecasting approach to cope with complex problems in megaprojects through the following three steps:

1. Identify a reference class for past but similar projects.
2. Establish a probability distribution for the selected reference class parameter to be forecasted.
3. Compare the specific project with the reference class distribution in order to establish the most likely outcome for the specific project.

As a result of the aim and objectives of this paper and concerns raised by the literature review, the following section presents methodologies used for modelling and assessing SE risks for similar megaproject cases.

Research Methodology

The methodologies adopted in this research are case studies, SD modelling and interview with experts involved in megaprojects.

Case study

To understand the subject of this research, systematic gathering of empirical data on Edinburgh Tram Network Project (ETNP) was carried out. The reason was to ensure unbiased judgement during analysis and for validation purposes. The choice of ETNP was based on the fact that, its development has been faced with numerous challenges relating to cost, time and specification and therefore has encountered cost and time overruns. The results obtained were initially used to describe and justify the SD methodologies adopted for this research, and furthermore provided descriptive features beyond studying surround context. The method further elaborated on detailed findings, and made accurate observation and rigorous collection of evidence on the SE risks impacts on the case project.

At the time of data collection, the project had been under development for four years and suffered time delays, cost overruns and other risks such as contractual disputes and utilities diversion problems. From the interview conducted, it was revealed that the project was improperly forecasted than initially expected and as a result, must face cost and time overruns. After long legal battles between the developer and the owner, the project has now been rescheduled to be completed in 2014, three years ahead of the original completion date in 2011 from line two to line one. When completed, it will be one of the most modern tram network projects in the world. Table 1 provides a summary of the initial basic information of the project.

Data collected were from project documents, online published Audit reports of the City Council, structured interviews and technical summaries. Information sought were basic project information, STEEP problems encountered and actual project performance relating to time, cost and specification achieved to date. Local business owners, operators, customers and project managers were interviewed in order to gain insight into STEEP problems relating to the project, verify the model structures and to obtain soft data that could not be obtained from project documents and published reports. The results were used to explain why delays and cost overruns occur in megaproject development by determining causes and effects through feedback loop diagrams.

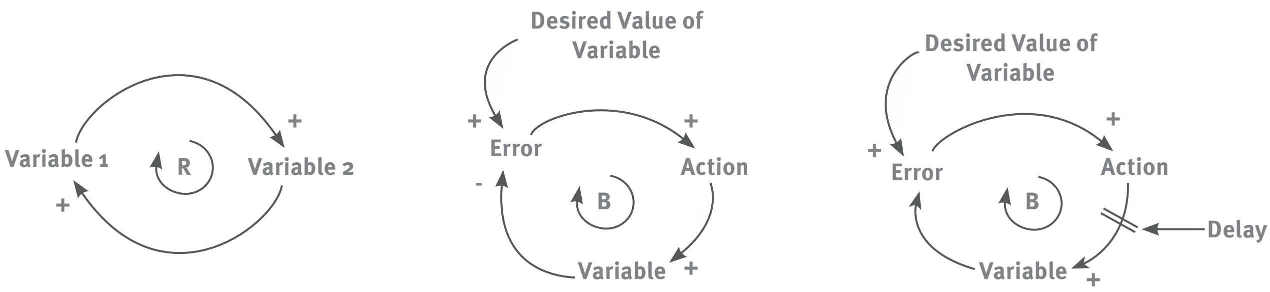
Project Title	Edinburgh tram network project
Purpose	• To support the local economy by improving accessibility. • To promote sustainability and reduce environmental damage caused by traffic. • To reduce traffic congestion. • To make the transport system safer and more secure. • To promote social benefits.
Scope	• To connect Edinburgh Airport to the City Centre • To link with development areas in North and West Edinburgh
Contractual Framework	• Development Partnering and Operating Franchise Agreement (DPOFA); • System Design Services (SDS); • Joint Revenue Committee (JRC); • Multi Utilities Diversion Framework Agreement (MUDFA); • Infrastructure provider and maintenance (Infraco); and • Vehicle supply and maintenance (Tramco).
Relevant physical dimension	• Total length: 24 km in two phases • Phase 1a: 18.5km, is underdevelopment (Case study) • Phase 1b: 5.5 km, to be developed later
Cost (£ million)	• Planned project budget 545 • Validated budget 776 • Cost variation 231
Year of completion	• Original planned date 2011 • Expected new date 2014

Table 1 **Basic information of Edinburgh tram network project, Source: Edinburgh Tram Project, the City of Edinburgh Council reportno. CEC/41/11-12/CE**

The systems dynamics

The systems dynamics (SD) methodology is adopted in this study. The SD methodology is a field created at MIT by computer pioneer Jay Forrester in mid 1950s for modeling and analyzing the behavior of complex social systems in an industrial context (Sterman, 2000). It was designed to help decision-makers learn about the structure and dynamics of complex systems, to design high leverage policies for sustained improvement, and to catalyze successful implementation and change. In recent years, the SD has been used by researchers and project managers to understand various social, economic and environmental systems in a holistic view (Rodrigues 1996; Towell 1993; Sycamore 1999; Mawby 2002; Love 2002; Ogunlana 2003 and Naseena 2006).

The system dynamics approach is primarily based on cause-effect relationship. This cause-effect relationship is explained with the help of stock, flow and feedback loops. Stocks and flows are used to model the flow of work and resources through the project. Feedback loops are used to model decisions and project management policies. System Dynamics can be used to model processes with two major characteristics: (1) those involving change over time, and (2) those involving feedback (Ogunlana 2003).



2a. A Reinforcing Loop   2b. A Balancing Loop   2c. A Balancing Loop with Delay

→	A cesual relathionship
+ (-)	Signs at the arrowheads indicate the effect is positively (negatively) related to the cause
//	Sign on the arrow indicates material and / or information delay
	R denotes Reinforcing loop and B, the Balancing loop

Figure 2 **The three components of system dynamics models**

The central concept of System Dynamics is to understand how the parts in a system interact with one another and how a change in one variable affects the other variable over time (Senge, 1990), which in turn affects the original variable (See Figure 2). Systems can be modeled in a qualitative and quantitative manner. The models are constructed from three basic building blocks: positive feedback or reinforcing loops, negative feedback or balancing loops, and delays. Positive loops (reinforcing loops) are self-reinforcing while negative loops (balancing loops) tend to counteract change. Delays introduce potential instability into the system.

Figure 2a shows a reinforcing loop, which is a structure that feeds on itself to produce growth or decline. Reinforcing loops correspond to positive feedback loops in control theory. An increase in variable 1 leads to an increase in variable 2 (as indicated by the "+" sign) and that leads to an additional increase in variable 1 and so on. The "+" sign does not mean the values necessarily increase, only that variable 1 and variable 2 will change in the same direction (polarity). If variable 1 decreases, then variable 2 will decrease. In the absence of external influences, both variable 1 and variable 2 will clearly grow or decline exponentially. Reinforcing loops generate growth, amplify deviations, and reinforce change.

A balancing loop (Figure 2b) is a structure that changes the current value of a system variable or a desired or reference variable through some action. It corresponds to a negative feedback loop in control theory. A (-) sign indicates

Researchers	Year	Summary
De-Marco, A. & Rafele, C.	2009	A feedback process to understand construction project performance
Nasirzadeh, Afshar and Khanzadi	2008	An approach for construction risk analysis
Mugeni-Balyejusa, B.	2006	Modelling changes in construction projects.
Howick, S.	2003	Disruption and delay in complex projects for litigation
Ogunlana, Sukhera and Li	2003	Performance enhancement in a construction organization.
Love, Holt, Shen, Li and Irani	2002	The need for understanding of how particular dynamics can hinder the performance of a project management system.
Park, M.	2002	Change management for fast-tracking construction projects
Chritamara. S and Ogunlana. S.	2002	Modelling of design and build construction projects
Rodrigues, A. and Bowers, J.	1996	A comparative analysis between two approaches to project management.

Table 2 **Applications of system dynamics in research into construction project management, Source: Boateng et al., 2012**

that the values of the variables change in opposite directions. The difference between the current value and the desired value is perceived as an error. An action proportional to the error is taken to decrease the error so that, over time, the current value approaches the desired value. The third basic element is a delay; this is used to model the time that elapses between cause and effect and is indicated by a double line (Figure 2c). Delays make it difficult to link cause and effect (dynamic complexity) and may result in unstable system behaviour.

In Systems Dynamics, verbal descriptions and causal loop diagrams are more qualitative; stock and flow diagrams and model equations are more quantitative ways to describe a dynamic situation. As systems Dynamics is largely based on the soft systems thinking, (learning paradigm), it is well suited to be applied on those managerial problems which are ambiguous and require better conceptualization and insight (Sushil 1993) than what the conventional methods such as PERT/CPM techniques can provide. As indicated in table 2, the SD has been successfully used in construction project related research (Nasirzadeh et al., 2008).

Unlike the conventional approach (PERT/CPM), where planners use human judgement to interpret their own mental models, the SD approach according to Sterman (1992), uses computer models to overcome limitations of the mental models. Sterman established that, the SD computer models are explicit and open to all to review; capable to compute the logical consequences of the modeller's assumptions; able to interrelate many factors simultaneously and finally, can be simulated under controlled conditions for analysts to conduct experiments outside the real system. Table 3 indicates some of the capability differences between the two approaches which make SD a preferred choice over the PERT/CPM in megaproject planning against SE risks.

Capability	PERT/CPM	System dynamic
Capturing managerial corrective actions	Low	Very high
Realistic actions for project acceleration	Low	Very high
Detailing level	High	Very high
Risks and uncertainty management	High	Very high
Evaluating impact of uncertainties	High	Very high
Evaluating decision level	High	Very high
Estimating accurate project cost, duration & resources	High	Very high
Work schedule	High	Very high
Project control and monitoring	Yes	Yes
Showing interrelationship	Yes	Yes
Accounting for feedback effects	Yes	Yes
Work specification	Yes	No
Assigning responsibilities	Yes	No
Handling multi interdependent components	No	Yes
Productivity impact consideration	No	Yes
Handling multiple feedback processes	No	Yes
Handling non-linear process relationship	No	Yes
Computational capability for predictions	No	Yes

Table 3 **Capability differences between PERT/CPM and the System dynamics tools / Based on desktop study**

Discussions

The model structure

The model is divided into five subsystems as Social, Technological, Economical; Environmental and Political (Figure 3). Each of these sub-systems consists of numerous variables and equations. Due to space limitation, the social and environmental (SE) subsystems are only considered in this study. The model boundary chart (Table 2) indicates detailed results of the variables under each of the two subsystems considered.

The model boundary chart

The model is bounded in the construction phase and for the developer. The boundary chart (see Table 4) is a chart which summarizes the scope of a model by categorizing the variables of identified SE risks into endogenous and exogenous.

Endogenous variables are those represented within the model with values determined or influenced by one or more of the independent variables in the system. Exogenous variable on other hand, are factors which are outside of the model of each subsystem. Although,

Model subsystem	Model variables	
	Endogenous	Exogenous
Social	• Multi-player/level decision making • Social issues • Social acceptability • Social grievances • Legal action • Reputational risks	• Construction disruptions • Need to relocate • Pedestrian and bicycle safety • Accessibility to families, friends and community resources • Choice of travel modes • Linkage between residence and job • Land and property value • Waste generation • Pollution (water, air etc...) • Dust • Transport issues (traffic) • Stakeholders satisfaction • Regulatory environment
Environmental	• Climate change • Construction disruption • Adverse environmental impacts	• Adverse climatic conditions • Ecological/social issues

Table 4 **SE Model boundary chart**

such variables have impacts on the outcome of the model, changes in the model do not affect them. The variables include those for the SE risk factors which impact on ETNP during construction.

Model construction

A typical system dynamics model goes through some standard steps. Although there will be variations depending on the nature of the problem and style of the modeller. The main steps for modelling in this study can be summarized (see Figure 4) as follows:

Problem identification and definition
1. Initial model development
2. Model verification (expert opinion)
3. Final model development
4. Model simulation (Analysis of model behaviour)
5. Model validation using software tools and case studies
6. Policy analysis, model use or implementation

Based on the results in table 4, the cause and effect diagrams in figure 5 were modelled with SD methodological

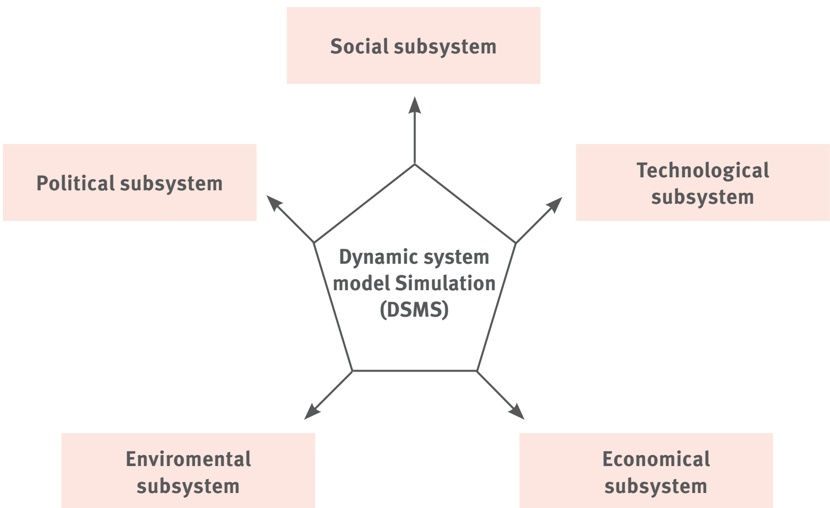


Figure 3 **Model breakdown structure**

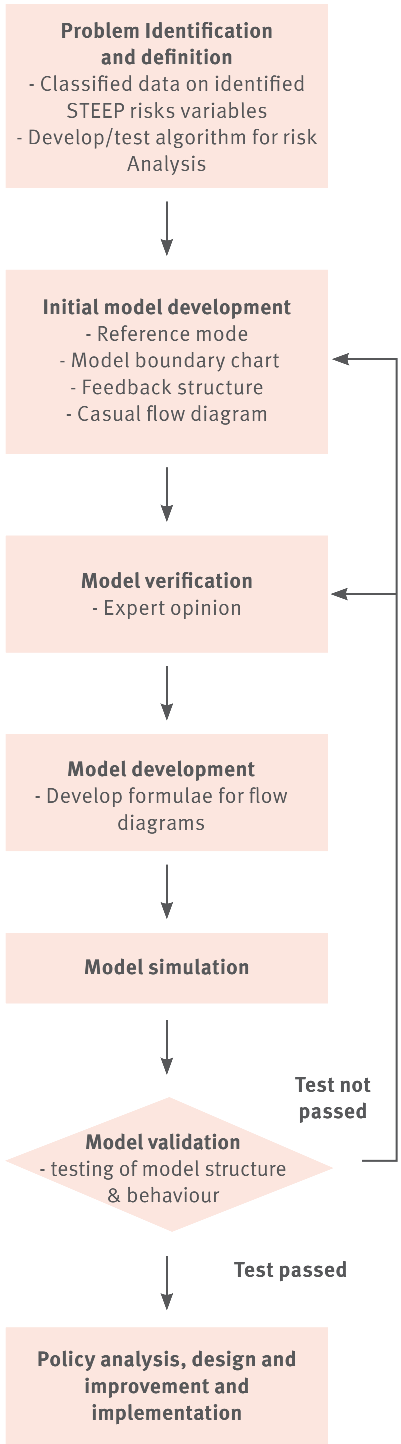


Figure 4 **SD modelling steps**

approach. In Figure 5a, social risks were generated through chains of complex web of numerous interconnected causes and effects from social issues, social grievances, multi- player/level decision making bodies, reputational risks and legal actions by society (NGOs and others) and from media attention during

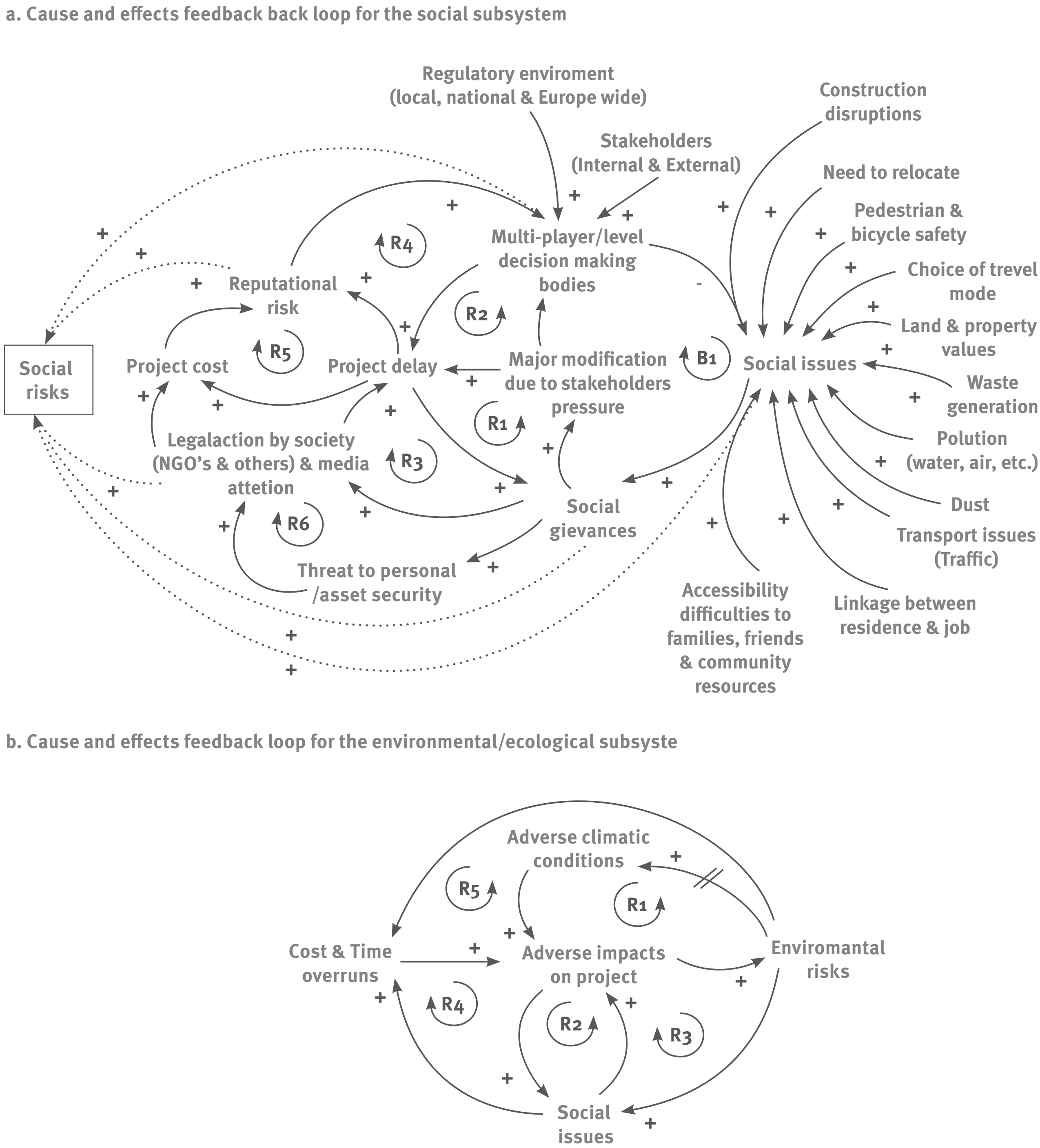


Figure 5 **Feedback structures for social and environmental subsystems**

development. On the other hand, figure 5b indicated adverse impacts on the project from climatic conditions and social issues. These impacts, however, led to environmental risks, a further impact on the social environment through to project cost and time overruns. The arrows indicate cause-effect relationship and have a plus (+) sign when the cause increases the effects while the minus (-) sign indicating a decrease of the effect from the cause. There are two feedback loops (R and B) in Figure 5. The loop R1 denotes a reinforcing loop or positive loop and shows increase in the system from the social grievances through major modification due to stakeholders' pressure to project delay thereby causing reinforcement within the system. The other loops with B signs indicate balancing or negative loop. In loop B1 for example, increased in multi-player/level decision making bodies will decrease social issues and social grievances. The practice will further reduce frequent modification to project scope due to stakeholders' pressure to project

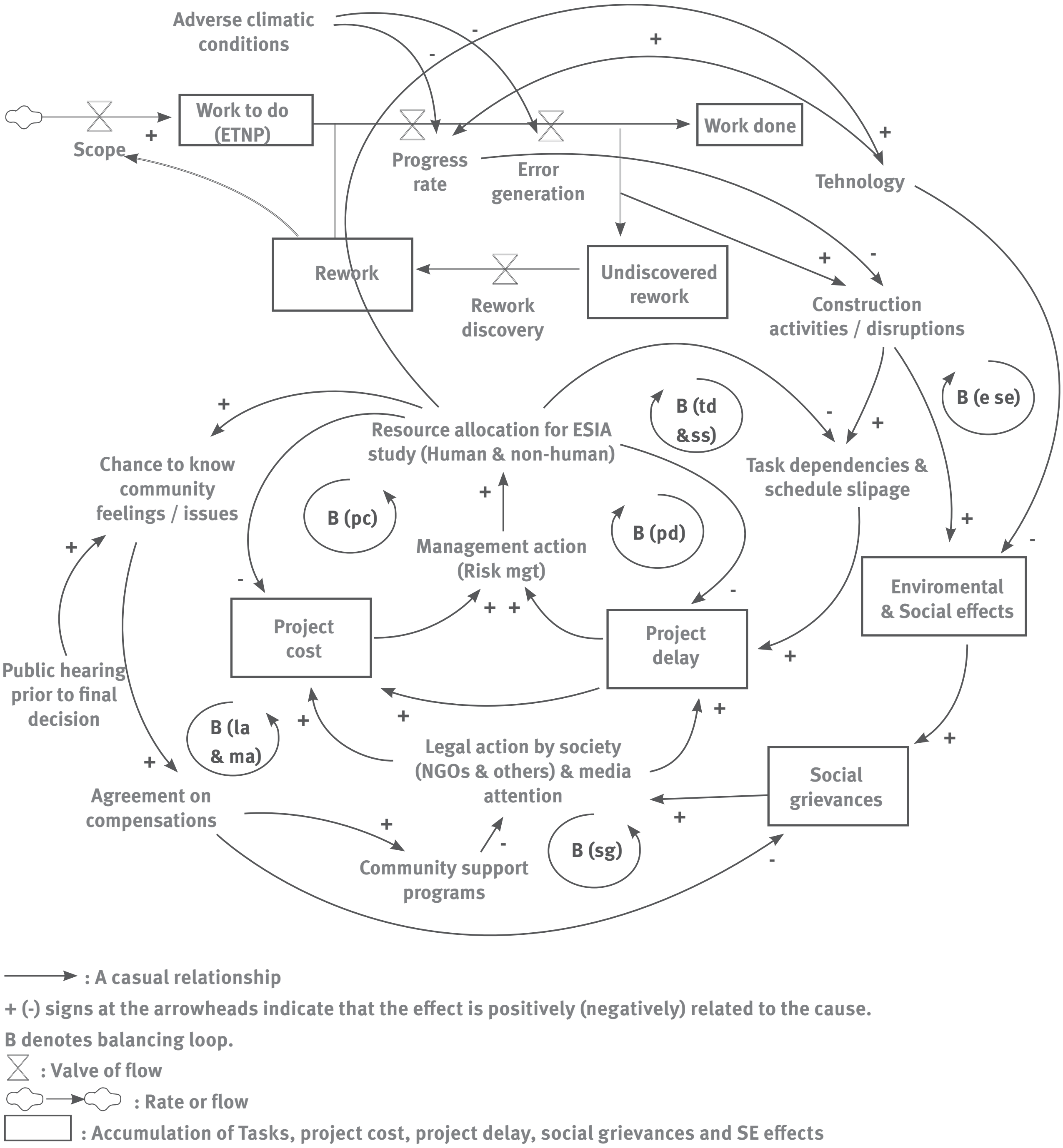


Figure 6 **Dynamic hypothesis demonstrating social and environmental risk management in megaproject construction**

on track. Complexities will occur when divergence views of regulatory bodies and stakeholders are not dynamically correlated, thereby causing chaotic time and cost overruns.

Dynamic hypothesis

Both qualitative and quantitative results which lead to SE risks in the case project were used to construct the final feedback model to address the systematic issues of time and cost overruns in megaproject construction. The SD models were set up in accordance with British Standards on risk management in order to provide a generic tool for risk management in megaproject development in five steps: risk management planning, risk identification, qualitative and quantitative risk analysis, risk response planning, risk monitoring and control.

▶ Step1.- Risk management planning
Within the SE risk management planning, Figure 5 and 6 allow for feedback loops concerning project delay and project cost overruns. These figures provide define structure levels of risk manage-

ment within the activities of project risk planning and can be use by planners to pro-actively test and improve the existing project plan such as forecasting and diagnosing the likely outcomes of the current plan.

▶ Step2. - Risk identification

The SD models can support risk identification in a qualitative level through the influence diagrams. Given SE as specific risks, it is possible to identify which feedback loops favour or counter the occurrences of such risks. In loop B (la & ma) (see Figure 6), the public participation in the Environmental and Social Impact Analysis (ESIA) drives public feelings and their feedback on the direct or indirect impacts of the project magnitude to be understood. This can help the Project management team to formulate and agree on what compensatory packages to be given out to the affected community by the tram construction. The identification of the project affected group and effective community support programs will also minimise legal actions by the society and thereby creates good relationship within the project environment.

▶ Step3. - Risk analysis

The influences shown in the models can further assist project managers of the tram network project to assess SE risks in both qualitative and quantitative manners. In the qualitative analysis, each feedback loop can be a dynamic force that pushes away from the risk occurrence. With regards to risk likelihood, magnitude and impacts, a simulation model can best be used to identify and capture full impacts of potential SE risks on the project. Further impacts of risks can be quantified and simulated to generate a wide range of estimates and scenarios to reflect the full impacts of the SE risks occurrences and impacts on Trams Network Project during construction.

▶ Step4. - Risk response planning

The models can be effectively used to support risk response planning in Tramline projects and other similar megaproject development in three ways.

Provide feedback perspective for SE risks identification.

Provide a better understanding of the multiple- factor causes of risks and a trace through the chain to identify further causes and effects.

Serve as powerful tools to support project managers to devise effective responses.

▶ Step5. - Risk monitoring and control

The models provide effective tools for risk monitoring and control. Through the cause and effects diagrams, early signs of unperceived risks emergences can be identified to avoid aggravation. In addition, simulated models can provide effective monitoring and control mechanism for risks diagnosis.

Conclusions

With the assistance of a practical survey, this paper has systematically examined major SE risks affecting the megaproject construction using Edinburgh Trams Network Project as a case study. The risk models developed in this paper, supported by examining real risk cases, provides an effective insight and clear picture of the SE risks involved in megaproject development and construction. The understanding of these SE risks is essential in order for planners to take proper risk management strategies.

The investigation of several practical risk management strategies demonstrates effective examples of adopting risk management principles to provide useful references to megaproject planners and developers or those overseas firms who are planning to operate their businesses in the UK. The findings and analysis in this paper would present valuable data for the initiating Government and local partners to have an in-depth understanding of the SE risk environment to the construction of megaprojects. Such understanding is vital for implementing further effective measures to ensure that the right direction of future development create a more attractive environment to all stakeholders to avoid project delay and cost overruns.

Future Research

To enhance the performance of the existing risk management processes, future research on Social, Technology, Economic, Ecology and Political (STEEP) risks in construction and engineering projects will be modelled using system dynamics methodology to aid multi-criteria decision making during risk management. The future research will also look into STEEP risks from more megaprojects to support the building of decision making to improve the understanding and accuracy of the management of megaprojects using system dynamic models.

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