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A dynamic system approach to risk analysis for megaproject delivery

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Abstract: This article describes a dynamic systems approach to quantitative risk assessment and simulation in megaprojects with regard to social, technical, economic, environmental, and political (STEEP) issues relating to sustainability at construction stage. A literature review was conducted to justify the needs for such a dynamic systems approach that originally integrates the functions of two sophisticated quantitative methods including the analytic network process (ANP) and the system dynamics (SD) for an advanced solution to tackle problems of overruns on budget and schedule (OBS) at the construction stage in megaproject delivery. The new dynamic systems approach called Sdanp is described in details with a theoretical framework and its technical procedure for application. This article finally provides an experimental case study on the Edinburgh Tram Network (ETN) project to demonstrate the usefulness of the Sdanp method and it also discusses its implementation to support risk management in megaproject delivery towards sustainability.

Keywords: Dynamics, Management, Planning & scheduling, Project management, Risk & probability analysis, Sustainability

(Note for Keywords: Please consider to add the following recommended keywords if this could be appropriate: Analytical network process, Construction management, Major project, Megaproject, System dynamics; otherwise please remove this note from the manuscript.)

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Acronyms

ANP	Analytic Network Process
BSI	British Standards Institution (British standards)
COST	Cooperation in Science and Technology
ERA	Environmental Risk Assessment
ETN	Edinburgh Tram Network (project)
MCDA	Multi-Criteria Decision Analysis
OBS	Overruns of Budget and Schedule
RAM	Risk Analysis Method
RI	Risk index
RPI	Risk Priority Index
SD	System Dynamics
STEEP	Social, Technical, Economic, Environmental and Political (aspects/issues/risks)
SWIFT	Structured What If Technique
TIE	Transport Initiatives Edinburgh
WQS	Weighted Quantitative Score

Glossary

The following technical terms and/or concepts are used in this article.

Megaproject. A capital project typically costing more than US\$1 billion.

Analytic Network Process (ANP). A generic multiple criteria decision analysis technique put forward and developed by Professor Thomas L. Saaty (1926-2017), a Distinguished University Professor at the University of Pittsburgh.

Project sustainability. The sustainability of one project in relation to the achievement of its goals on social, technical, economic, environmental and political (STEEP) aspects in short and longer term (Chen, 2012). Megaproject sustainability was put forward by Chen (2012) during his collaborative research with colleagues at the COST Action TU1003 focusing on the effective design and delivery of megaprojects in the European Union.

Risk assessment framework. A process or analysis oriented framework that can be use in one particular professional practice so as to facilitate the implementation of a series of planned actions on risk assessment.

Sustainability risk. The risk posed to sustainability.

System Dynamics (SD). A predictive approach to mapping and simulating the process and consequence of a complex system based on the nonlinear behaviour of its interconnected elements over time. This method was originally put forward and developed by Professor Jay W. Forrester of the Massachusetts Institute of Technology (MIT) in 1950s (Forrester, 1958).

1. Introduction

This article describes a recent research into an innovative approach to holistic risk analysis with regard to major challenges on budget, schedule and sustainability in megaproject delivery (Chen, 2019). The research focuses on a new multiple risk oriented dynamic system approach called Sdanp, and it has been originally developed and examined in an experimental case study on the Edinburgh Tram Network (ETN) project. As a controversial construction project (Swanson, 2018), the ETN project is a mega transport project with a total cost of £776 million but significant OBS, which happened in the delivery of many other megaprojects. While there have been numerous discussions, debates, inquiries, and research in relation to megaproject delivery across the world, it is the initiative of the authors of this article to explore a new technique solution that can help the project management team to identify and tackle major risks that have a significant threat of OBS and a huge challenge on sustainability in the process of megaproject delivery. In other words, the research described here is trying to fill an identified knowledge gap (see Annex I) based on the authors' experiences and extensive literature review in megaproject risk assessment, which can support risk control against overruns and sustainability with regard to enhanced competence in project management. There are two objectives of the described research, and these include

- To explore and model problems on overruns, which are presumably caused by project associated risks to budget, schedule and performance, etc., and
- To provide a new technical solution that can effectively support risk management in megaproject delivery.

The knowledge gained from this research could be useful to improve the accuracy of risks analysis and estimation at an early stage of megaproject delivery, thereby reducing the problem of OBS.

This article describes the research in two parts, including Sdanp method for risk assessment and simulation in megaproject delivery, and an experimental case study on the ETN project. The Sdanp method is a new technical solution to tackle the consistent problem of OBS in megaproject delivery. For academics, it provides a new theoretical framework that offers a platform to incorporate tangible and intangible risk variables into an interconnected calculation process successively using ANP first to prioritise project risks, and SD afterwards to predict the consequences of those risks over time in megaproject delivery. For practitioners, it challenges the paradigm of considering new methods for enhanced risk analysis in megaproject management. When compared to traditional risks analysis methods, results obtained from using the Sdanp method through experiment has indicated its uniqueness to provide critical information on prioritized risk factors and predicated OBS to timely inform decision making on risk management at planning stage in megaproject delivery. According to the experimental case study, the Sdanp method is promising to predict overruns with a higher accuracy, and it appears to be a superior solution for solving the dynamic complexities of risks in megaproject delivery. It is therefore expected that this research can well inform further research and practice with a new tested technical solution for megaproject risk analysis.

2. Background

This research was established through an extensive literature review at the initial stage in order to identify the knowledge gap (see Annex I), and justify its aim and objectives, which focuses on developing a new dynamic systems approach to risk analysis that can support relevant decision making in megaproject management. The review has three main parts to support deep understanding of current research into the use of ANP and SD and their relevance and potential in areas relating to megaproject management in the context of risk analysis against OBS, which are deemed as major challenges in megaproject delivery (Chen, 2019). It was a research assumption that a combined use of the two powerful techniques can form a useful tool to effectively tackle the overrun problem through more dependable risk analysis for megaproject delivery. A brief description about the two techniques is give below with regard to the aim and objectives of the described research.

2.1 Analytic Network Process (ANP)

Concept. The ANP method was originally put forward and developed by Prof. Thomas L. Saaty (1996), and it is one of the most powerful multi-criteria decision analysis (MCDA) techniques available at present that can enable an effective use of group based expert judgments. According to Prof. Saaty (2005), ANP is a systematic method that uses both quantitative and qualitative measurement across interconnected factors chosen for decision making upon multiple criteria, and it has been further described as one of the most

powerful synthesis methodologies for combining judgment and data to effectively rank options and predict outcomes (CDF, 2019).

Process. As a technique to support MCDA, the ANP has a formal procedure, which consists of several major steps, including

- Define a decision-making goal, and a set of evaluation criteria for comparing alternatives under the goal,
- Set up an ANP model to connect all chosen evaluation criteria, including main criteria and their sub-criteria, through pairwise comparison based on experts' judgments,
- Run the calculation of super matrix generated from the ANP model, and
- Select, from the calculation result, the most competitive alternative as justified decision.

An ANP model is essential for the use of MCDA technique to support decision making, and it is an interconnected network structure of criteria clusters and their nodes. For this structure, clusters are alternatives under evaluation and main evaluation criteria, and nodes are sub evaluation criteria. These components are elements of an ANP model, and grouped into interconnected clusters named under a category of main evaluation criteria. In the process to develop an ANP model, all elements of the network can be connected, through either subjective or objective way, to incorporate feedback and interdependent relationships within and between clusters. This mechanism can provide a more natural way as per human experts' decision-making process to model problems with complex characteristics in an organised cognitive environment, and can ensure a more objective concept and procedure for predefined goals in decision making, which can lead to the most influential choice in real world. In addition to the theory of this natural way to dealing with complex decision making questions, inputs from experts to an ANP model can ensure a synergetic result towards probably the most dependable outcome with high accuracy that people can expect to achieve in decision making.

Relevant applications. It was an initiative started in the early 2000s (Chen, 2007) to apply ANP in academic research into answering decision-making questions in relation to construction management. It has been found through published research that areas, for which ANP can be applied and useful to support decision making for construction management, include:

- Environmental priority evaluation for construction planning in order to eliminate adverse impacts caused by construction activities (Chen et al., 2003),
- Selection of contractor for client to ensure the performance of project delivery (Cheng and Li, 2004),
- Selection of project for developer to engage on new development (Cheng and Li, 2005),
- Value oriented assessment of building design product to support decision making at design stage (Chen *et al.*, 2007 and 2009),
- Vendor evaluation at procurement stage for sustainable construction (Chen *et al.*, 2008),
- Risk assessment for the analysis of optional development plans in urban regeneration (Chen and Khumpaisal, 2009),
- Prioritization of marketing activity for construction companies (Polat and Donmez, 2010)
- Environmental risk assessment on location selection for international hub airport (Chen *et al.*, 2011),
- Maturity assessment for risk management in large construction project (Jia *et al.*, 2013),
- Supplier selection for construction and civil engineering companies (Eshtehardian *et al.*, 2013),
- Evaluation of different demolition plans for reconstruction project (Chen *et al.*, 2014), and
- Prioritization of sustainability oriented risks in megaproject delivery (Boateng *et al.*, 2015).
- Selection of project for construction contractor to participate (Lin and Yang, 2016)

Potential A. These applications have examined the usefulness of ANP to improve the quality of decision making in construction management with regard to the need to incorporate an effective measure of interactions among chosen evaluation criteria. In addition to these construction management oriented experimental studies, academic research has also demonstrated the potential of ANP for decision making in other related areas such as the performance evaluation of research and development project (Tohumcu and Karasakal, 2010), location selection (Chen *et al.*, 2008; Yeh and Huang, 2014), plant maintenance (Kumar and Maiti, 2012), the choice of outsourcing services (Tjader *et al.*, 2014), the evaluation of long term performances of production (Pourjavad and Shirouyehzad, 2014), the selection of product service systems (Lee *et al.*, 2015), and financial forecasting (Shen and Tzeng, 2015), etc.; further application oriented research in areas relating to construction management is therefore expected.

Potential B. It has also been noticed from ANP related research that this MCDA technique has been integrated with other analytic techniques to form more powerful decision making support. For example, Wey and Wu (2007) made the use of ANP priorities with goal programming in resource allocation for transportation infrastructure development, and this resource allocation problem was further studied by a combination of Monte Carlo simulation with ANP through uncertainty analysis in transportation infrastructure planning (Liang and Wey, 2013). In addition to integrating ANP with other analytic techniques to deal with complex decision making problems, it has also been highlighted in previous research (Chen *et al.*, 2008) that a database with a collection of experts' knowledge/judgments in a specific area can be used to support the efficiency of an ANP model. It is therefore further anticipated to have a well-informed MCDA process, which is capable to deal with complex problems in construction management, can be realised through the integral use of ANP and other analytic techniques to be underpinned by the database of accumulated expert knowledge over longer term.

Potential C. It has been well identified through literature review that the ANP method has a precise language to quantitatively describe the interconnected issues as components of a decision making problem and their realistic interrelationships, and it is capable to handle feedbacks and interdependencies, which always exist in complex systems like the set of STEEP risks in megaproject delivery. It can therefore leverage for this research because of its significant efficiency with expected dependence to identify priorities among an extensive number of risk factors involved in a ranking list. This ranking list can be further used to inform risk analysis with other techniques such as a systemic simulation, which incorporates other useful analytic techniques as identified in literature review to form better decision making support. In addition, alternative methods such as discriminant analysis and artificial neural network were considered but not adopted in this research, and this was based on considerations on the lack of not only historic data from previous megaprojects to support the experimental case study, but also desired explanatory characteristics for risk analysis.

2.2 System Dynamics (SD)

Concept. The SD method was originally put forward and developed by Prof. Jay W. Forrester (1971) in the mid-1950s. It is a method for modelling and analysing the behaviour of complex social systems in an industrial context (Sterman, 2000; Morecroft, 2015) so as to help decision-makers on both engineering and management side learn holistically about the structure and dynamics of complex systems; and this method can also help leverage policies and strategies making at a high level, and catalyse successful implementation and substantial changes in the meantime.

Process. The SD process generally consists of five key steps (Duggan, 2016), including

- Articulate the problem to be addressed in connection to essential inputs such as important variables, appropriate time horizon, and historical data, etc.
- Propose dynamic hypothesis to identify the stock, flow and feedback structures that can best explain the problematic behaviour through causal loop diagrams,
- Build simulation model formulated with the stock and flow structure and decision rules,
- Test simulation model in comparison to the known reference models and its robustness under extreme conditions, and
- Design and evaluate policy through the use of simulation model to perform what-if analysis according to decision rules, strategies and structures that could be implemented in the real-world.

Relevant applications. It has been found through literature review that SD has been adopted in both academic research and professional practice in many areas of project management (Sterman, 1992; Towill, 1993; Rodrigues and Bowers, 1996; Sycamore and Collofello, 1999; Mawby and Stupples, 2002; Williams *et al.*, 2003) in order to better understand various social, economic and environmental systems in a holistic way through simulation. In the field of construction management, there have been a significant number of experimental studies on the application of this method, and areas of SD oriented research include

- Dynamic reasoning for civil engineering contracts (Saeed and Brooke, 1996),
- The dynamics of design error induced rework in construction (Love *et al.*, 2000),
- Change and rework in construction project management systems (Love *et al.*, 2002),
- Performance enhancement in a construction organisation (Ogunlana *et al.*, 2003),
- Innovations in construction (Park *et al.*, 2004),
- Construction project management (Lyneis and Ford, 2007),
- Impact assessment of different risks on project objectives (Nasirzadeh *et al.*, 2008a and 2008b),

- Impact analysis of weather conditions on construction activities (Boateng *et al.*, 2012),
- Risk assessment at the construction stage of megaprojects (Boateng *et al.*, 2013),
- Complexity management of construction information to improve performance for SMEs on construction projects (Khan *et al.*, 2016), and
- Modelling critical risk factors for Indian construction project (Mhatre *et al.*, 2017).

Potential. It has been particularly noticed that Ford *et al.* (2007) adopted SD focusing on three project controls, including exerting pressure on project staff to work faster, having staff work overtime, and hiring additional staff, to minimize OBS in construction project. This research initiative has demonstrated the effectiveness of SD in dealing with the overrun problem in construction with a particular small scale of influential factors, and it has not been expanded to tackle overruns in megaprojects with regard to the demand on SD for project risk management (Gray and Shahidi, 2011) considering a comprehensive set of project risks and their multiplied impacts (Bañuls *et al.*, 2017). This has therefore left a space for further research.

2.3 The integration of ANP and SD

It is a research question regarding whether it is useful to integrate the two powerful techniques, i.e., ANP and SD, to better deal with complex problems such as risk analysis to support decision making and management performance in megaproject delivery. This question was answered from literature review on the feasibility and effectiveness of integrating ANP and SD, and a few research initiatives have been found. For example,

- Tesfamariam and Lindberg (2005) applied the two methods for the aggregate analysis of manufacturing systems;
- Xu (2011) presented a research to use the two techniques to better explain the interaction and variation of sustainability indicators in the development of residential buildings; and
- Chou (2015) developed a multiple-technique approach to improving performance measurement and management system.

In addition, it has been further noticed that alternative MCDA techniques such as the interpretive ranking process (IRP) is also integrated with SD to model critical risk factors for Indian construction project (Mhatre *et al.*, 2017). Consequently, it was concluded from the authors' literature review that it is a research initiative to integrate ANP and SD for enhanced risk analysis in construction project management with regard to the particularly complex construction system.

3. Methodology

The methodology to guide the research described in this article was developed according to literature review in areas relating to methods for risks analysis (assessment and simulation) and need for integrated risk assessment and simulation for risk management in megaproject delivery within both normal and extreme project environment. It consists of the theoretical framework of the so called Sdanp method, which has a route of risk prioritisation through ANP assessment, and a route of risk prediction through SD simulation. The details of this methodology are provided below.

3.1 Theoretical framework

The Sdanp framework is a new theoretical model integrating multiple risk assessment with system simulation to support risk management in megaproject delivery. As illustrated in Figure 1, it comprises of connected mechanisms with interfaces of ANP assessment and SD simulation, and the two interconnected methodological routes for risk assessment and simulation respectively are also connected with a megaproject database that provides necessary data and information.

Figure 1: Sdanp framework for risk assessment and simulation

The Sdanp method and its models were developed by incorporating a holistic set of risk related technical parameters, and these include not only tangibles such as work-to-do, project cost, but also intangibles such as uncertainties, grievances and inadequate project complexity analysis in a novel risk analysis process. This risk analysis process involves two technical routes, including the ANP approach to prioritising risks in relation to project delivery, and the SD approach to simulating the dynamics of such risks within the project environment. In the research described in this article, these two technical routes are integrated within a new theoretical framework to increase the analytical and the dynamic capabilities over traditional risk analysis methods (BSI, 2010), which include analytical parameters such as cost, duration, quality, and probabilities, etc., but have a limitation to incorporate heuristics in risk analysis.

With regards to the complexity and dynamics coupled with new procurement methods in megaproject delivery (Hart, 2015; Hickman, *et al.*, 2015; Gerrard and Kings, 2017), the current tendency in project risk analysis is to use risk quantification and modelling more as vehicles to enhance risk response planning amongst multi-disciplinary project team members. For example, Davies *et al.* (2014) emphasised that an effective risk management approach through innovation can provide a framework to identify and assess potential risks so that response actions can be taken to mitigate them. However, many risk management approaches currently adopted in practice are not efficient enough to analyse and assess risks in a dynamical way (Too and Too, 2010). As a result, previous risk analysis may normally exclude the reality in practice where communicating construction project risks becomes poor, incomplete, and inconsistent throughout the construction supply chain for the project, and this may lead to significant problems such as OBS in megaproject delivery. It is therefore necessary to find advanced technical solutions to tackle this challenge, and the Sdanp method described in this article is one solution that the authors have explored for sustainable construction in megaproject delivery.

In the process to develop the Sdanp method, the authors adopted a holistic approach to combining quasi-ethnography, interviews and the literature to identify various risk factors in relation to multiply interconnected social, technical, economic, environmental and political (STEEP) issues (Flyvbjerg *et al.*, 2003; Chen, 2007; Chen and Khumpaisal, 2009; Chen *et al.*, 2014; Hickman *et al.*, 2015; Flyvbjerg, 2017; Cepeda *et al.*, 2018) that have significant impacts on project performance at construction stage under major challenges in megaproject delivery (Chen, 2019). All identified risk factors were then prioritised using ANP to establish a set of the most salient variables, i.e., STEEP risk factors, on the case project for experimental study. The selected risk factors with priority from ANP were then modelled through the route of SD to appraise their measured impact on the cost, time and quality performance of the case project overtime.

The Sdanp framework has two main technical routes connecting to the megaproject database, and they are an ANP route for risk periodization based on multi-criteria assessment, and a SD route for risk predication based on system simulation. A brief description about the two technical routes and megaproject database are provided below.

3.2 Risk assessment

ANP is adopted here to prioritise risk factors identified under STEEP regime in megaproject delivery. As illustrated in Figure 1, the framework has set up a specific ANP route to make a ranking list of potential project risks based on their relative importance through ANP assessment. As illustrated in Figure 1, the ANP procedure adopted in this framework consists of eight steps. Among these steps, there are five main steps, including

- Questionnaire survey to collect experts' qualitative and quantitative judgments on risk factors (See Annex for a list of risk factors selected for the ANP model developed in this research.),
- Construction of model structure (see Figure 2),
- Pairwise comparisons across clusters and elements/nodes of the model based on accumulated experts' judgments,
- Criteria normalization through super-matrix calculation within the Super Decisions software, and
- Risk prioritization based on risk priority index (RPI) (see Equation 1), which is a new risk assessment parameter derived from ANP.

Figure 2: ANP model for risk prioritization

The RPI put forward from this research is calculated by using Equation 1, which is to support final decision making by providing a ranking list of risk factors. The criterion to make this selection is the weights of alternatives, i.e., risk factors. Those weights are derived from a synthesised super-matrix in ANP model, and it was performed through using the Super Decisions software.

$$RPI_i = \sum_{j=1}^3 (W_{i,j(C,T,Q)} \times R_{i,j}) \quad (1)$$

Where

- RPI_i represents the global priority of risk i ,
- W_{ij} is the weight of the criterion j ($j \in [1,3]$) for risk i with regard to project cost, time and quality respectively, and
- R_{ij} is the local priority derived from supermaxim calculation in ANP.

The RPI is a new scientific way to measure the propriety of a risk factor within a set of project risks. This measurement, in comparison with rating method widely adopted in risk assessment, yields a different result through a comprehensive calculation on interactions inside a risk set and a combination of risk impact on critical project management performance covering cost, time and quality. The list of prioritized risks according to RPI is therefore more reliable than the one purely relies on limited subjective judgments, although the presentation of the risk list can be the same under a categorisation that describes risk impact as very high, high, medium or moderate, low and very low impact categories (Saaty, 1991). As illustrated in Figure 1, prioritized risks can be further useful within the Sdanp framework as an input to not only SD route for risk prediction but also an informed risk management in megaproject delivery.

3.3 Risk prediction

SD is adopted in the Sdanp framework to predict the consequences of interactive STEEP risks upon megaproject delivery through simulation. As illustrated in Figure 1, the framework has set up a specific SD route to derive useful information from systematic simulation. The SD procedure adopted in this framework consists of six steps. Among these steps, there are three main steps, including model construction through developing a causal loop diagrams for the entire system of STEEP risks with an input from ANP upon RPIs, simulation based on verified SD model, and data validation to justify simulation results.

Figure 3 illustrates an exemplar SD model developed in this research to describe interactions among all STEEP risk factors selected for experimental case study. In utilizing SD to model systems in both qualitative and quantitative manner, the model and its sub models can be built using three essential building blocks (see Figure 4), including

- Positive feedback or reinforcing loops which are self-reinforcing,
- Negative feedback or balancing loops which tend to counteract change, and
- Delays which indicate potential instability in the system.

This initial SD model was developed using data and information collected from both of the megaproject database and ANP. The concept and target is to understand in both qualitative and quantitative way regarding how individual parts interact with one another in relation to possible interactions in a megaproject risk system.

Figure 4 further illustrates the three essential components of the SD model. It is to show how a change in one variable can affect the other over time, and in turn affects the original variable. A brief description about the three model components are provided below.

Legend:

- .. —————> A causal relationship
- + (-) signs at the arrowheads indicate that the effect is positively (negatively) related to the cause.
- R denotes reinforcing (positive) loop and B, the balancing (negative) loop
- // sign on the arrow indicates material and/or information delay

Figure 4: Three components of SD models

Reinforcing loops. A reinforcing loop generally feeds on itself to produce a growth in a system to correspond to positive feedback loops in control theory. As illustrated in Figure 4a, an increase, which is indicated by sign +, in Variable A leads to an increase in Variable B and that in turn leads to additional increase in Variable A and so on. The sign + marked on the head of an arrow curve does not necessarily mean that values produced in the system will increase, and it just means that Variable A and Variable B will change in the same direction of polarity. If Variable A decreases, then Variable B will decrease. In the absence of external influences, both Variable A and Variable B will clearly grow or decline exponentially. Reinforcing loops generate growth, amplify deviations, and reinforce change inside a dynamic system conceptualised in the SD model.

Balancing loops. A balancing loop illustrated in Figure 4b is a structure that changes the current value of a system variable or a desired or reference variable through some actions. It corresponds to a negative feedback loop in control theory. The sign - indicates that the value of a variable 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 the current value approaches the desired value over time.

Time delays. The time delay as illustrated in Figure 4c is used to model the time that elapses between cause and effect. A time delay indicated by a double line can make it difficult to link cause and effect (dynamic complexity) and may result in unstable system behaviour.

Based on a verified causal loop diagram as illustrated in Figure 3, a stock and flow diagram (see Figure 5) can then be developed using the 'n' priority risks derived from the ANP computation and the inputs which the experts provided to facilitate in-depth stock and flow modelling and risk simulation over time.

Figure 5: A simple stock and flow model for social risks

The governing equations used to calculate the entire system parameters can also be formulated at this point. To understand accumulation process of inflow of uncertainties, it is important to know the mathematical meaning used to integrate the flow of risk influences into the system. Based on a mathematical definition of the integral, the level of risk impacts inside a stock will be the integration of total flows of uncertainties on the stock (See Equation 2).

$$\text{Stock}(t) = \int_0^t [\text{flows}_{\text{total}}(s)] ds \quad (2)$$

Where $\int_0^t [\text{flows}_{\text{total}}(s)]$ is a function of the total flow in the system.

Inflow (Uncertainty) indicates the increasing amount of risk level in the stock (Risk accumulation container). In the other hand, outflow (certainty) decreases the level of risk impacts in the stock. Using RPI as the quantity of risk impact level in the stock at the initial time, the equation above becomes the following:

$$\text{Stock}(t) = \int_0^t [\text{flows}_{\text{total}}(s) - \text{Outflow}(s)] ds + \text{Stock}(0) \quad (3)$$

Where $\text{Stock}(0)$ is the stock of risk impact level (RPI) at the initial time ($t = 0$).

In SD, variable descriptions and causal loop diagrams are more qualitative, while stock and flow diagrams and as well as model equations are more quantitative to describe the dynamic situation of a complex system. Since SD is largely based on systematic thinking, it is well suited to be applied on those managerial problems which are ambiguous and require better conceptualization and insight (Madachy, 2007), and this was another reason why it was chosen to analyze risks in the system of megaproject management.

3.3 Megaproject database

The megaproject database illustrated in Figure 1 is used to store data and information of identified STEEP risks in order to support effective Sdanp processes for useful information to be derived from risk assessment and simulation. The database contains highly specialized knowledge in problem areas from identified sources of data and information provided by experts and obtained from literature respectively. In addition to this, it also has source documents of similar past projects, data and information from the ongoing case project for experimental study. The megaproject database was initially constructed by accumulating data and information under the structured risk factors, which were listed in Annex, and those data and information were collected through extensive literature review and questionnaire-based survey in different processes for risk assessment and simulation within Sdanp framework in the experimental case study, which is described below in Section 4. In this experimental case study, the database was used to facilitate the use of relevant data and information transferred through interfaces into both ANP model and SD model.

4. Experimental case study

The Sdanp method was subjected to a case study to measure its effectiveness in performing risk analysis in megaproject delivery, and the ETN project was chosen for experimental case study. The description about this experimental case study focuses on general information about the project, STEEP risks identified through literature review and field study, two models developed within the Sdanp framework, and results from the experiment.

4.1 The ETN project

The ETN project initially consisted of three lines and was designed to run through the City of Edinburgh Council (CEC). According to the tram documentation (CEC, 2019), the entire tram line is to be built in several phases, including

- Phase 1a incorporated the construction of an 18.5-kilometre tramway from Newhaven to the Edinburgh Airport through Princes Street of the Edinburgh city centre, combining parts of Lines 1 and 2.
- Phase 1b involved the construction of a 5.6-kilometre tramway from Haymarket to Granton Square via Crewe Toll, comprising most of the remainder of Line 1.
- Phase 2 linked Granton Square and Newhaven together, completing the Line 1 loop.
- Phase 3 would have the airport line extended to Newbridge, completing Line 2.

The Line 1 of the tramway network involved a circular route running around the northern suburbs, while the other two formed radial routes running out to Newbridge in the west and to Newcraighall in the south. All lines were designed to run through the city centre of Edinburgh. The new construction also involved related projects, including new tramway bridges, retaining walls, viaducts, the tram depot and control centre, electrical sub stations to provide power to the overhead lines at 750 volts, track laying and tram stops.

The initial contract cost of the ETN project was estimated on £545 million with a contract period of three years. The project was procured using a turnkey contract. The client, i.e. the CEC used a private limited company known as the Transport Initiatives Edinburgh (TIE) to deliver the tram project. Until August 2011, the ETN project was overseen by TIE, which was responsible for project and dedicated to manage the construction of the tramway. Further role of TIE was to administer, integrate and coordinate consultants and the principal contractor, i.e. a consortium of Bilfinger Berger and Siemens involved in the project.

By February 2011, contractual disputes and further utility diversion works resulted in significant time delays to the project beyond the originally planned programme. In late 2011, TIE was released from managing the ETN project. Turner and Townsend, the project management consultant was brought in by the CEC to ensure effective oversight and delivery of the project. Work in 2012 continued smoothly on schedule with a new governance structure under the management of Turner and Townsend until the project was completed in the summer of 2014.

4.2 STEEP risks

It can be widely recognised that megaproject are posed to risks in relation to STEEP issues. Risks associated with STEEP issues in the ETN project were identified in case study in order to set up models using ANP and SD. All these STEEP issues were considered in risk analysis so as to evaluate their impacts on project's performance controlled upon critical management domains, including cost, time and quality (PMI, 2016). A list of STEEP risks against megaproject delivery is given in Annex II. Based on all identified STEEP risks on the ETN project, an entire Sdanp model was developed using ANP and SD respectively.

4.3 Sdanp model

The Sdanp model developed for this experimental case study consists of one ANP model (see Figure 2), which was set up within the Super Decisions software environment, and one SD model (see Figure 3), which was set up within the Vensim DSS software environment. The two models were developed and integrated inside the Sdanp framework illustrated in Figure 1.

The SD model was constructed under RPIs derived from ANP model. Figure 3 illustrates a high-level causal loop diagram developed to demonstrate the entire project risk dynamics of the ETN project during construction. Variables in this diagram were causally related in the form of loops and had either no influence or a positive/negative influence on another risk factor. As a result of interconnections across many system variables (entities) and loops, the ETN project is said to belong to a class of complex dynamic systems that, according to Sterman (1992), exhibit the characteristics of being complex with multiple components, highly dynamic, involved multiple feedback processes, involved non-linear relationships and had both "hard" and "soft" data. Drawing from the causal loop diagram and its subsystems, qualitative risks causal loop diagrams were converted into SD models to evaluate the physical interactions of risk variables in the entire project system. Thereafter, RPIs (see Table 1) derived from ANP were incorporated into stock

and flow diagrams by using Vensim DSS software to simulate the dynamics of risk effects and impacts on project cost, time and quality during construction over time.

As a proven powerful MCDA technique, the ANP is capable to evaluate criteria and assign ratings to risks factors within the model illustrated in Figure 2. It can further lead to the selection of most risky factors acceptable to decision makers during the establishment of a set of RPIs (see Table 1) for the entire project. However, there is one area that needs greater attention to its application in decision making, and it is how to use the RPI obtained from pairwise comparisons and the synthesised super-matrix to perform risk analysis over time in order to anticipate and deal with the future more successfully through risk impact prediction and planning. To bridge this gap, SD is adopted to integrate the RPI from experience based ANP assessment into interaction driven systematic simulation in order to solve important problems concerning nonlinear dynamics and feedback control of risks behaviour in a complex megaproject delivery system.

In the dynamic system simulation, trend analysis was given priority and numbers do not normally have much significance, however, the numbers should be, as far as possible, close to the real life situations. In the context of risks modelling, inputs from ANP, i.e., RPIs, to the simulation system were adopted for the SD model; and this formed a unique connection in using the two techniques in risk analysis.

4.4 Experiment results

Experimental results from Sdanp modelling based on both ANP and SD model are shown in Table 1 and Figure 6. Outputs shown in Table 1 reveal dynamic simulation results under the following given time bounds and units of measurement for system variables:

- The initial time for the simulation: 2008, Unit: Year
- The final time for the simulation: 2015, Unit: Year
- The time step for the simulation: 0.125, Unit: Year
- Unit of measurement for system variables: Dimensionless

According to experimental results, it is clear that project time and cost are all impacted by STEEP risks. It has been found through this experiment that the consequence of OBS in the ETN project can be interpreted from these experimental results in connection with lessons learned for further practice on megaproject management against risks. Interpretations about the experimental results are given below in relation to three important issues, including the impact of STEEP risks, OBS, and the quality of project management.

Impact of risks. The mean impact levels of all risks in succession from RPIs, including P_{R1} to P_{R5} , on the ETN project were revealed to be 19.00%, 40.48%, 21.50%, 14.86% and 35.20% (see Table 1) for individual STEEP risks respectively. In addition, ‘time’ was found the most sensitive factor to the impact of economic, environmental and political risks whilst ‘cost’ was sensitive to the impact of the economic, environmental, political and social risks. On the other hand, ‘quality’ of project management was sensitive to the economic, environmental and political risks.

Table 1: Summary of outputs from Sdanp analysis

Risks		RPI (%)	Estimated level of risk (%)					
Cluster	Code		Min	Max	Mean	Median	SD	Norm
Social risks	P_{R1}	0.13	-31.00	48.00	19.00	20.00	18.00	96.00
Technical risks	P_{R2}	0.30	30.00	55.69	40.48	39.28	7.41	18.31
Economic risks	P_{R3}	0.25	1.72	33.00	21.51	26.07	10.73	49.86
Environmental risks	P_{R4}	0.16	6.59	18.78	14.86	14.86	16.39	3.85
Political risks	P_{R5}	0.17	17.00	42.10	35.20	37.70	7.04	20.00

Figure 6: Measured impacts of STEEP risks

Overruns on budget and schedule (OBS). For practical reasons, empirical tests were conducted to examine the ability of the STEEP model to match the historical data of the case study project. Information gathered from the real system was compared to the simulated results. As Table 2 indicates, the total level of risks impacted on the ETN project which resulted to OBS and project quality deficiency is 49.53% on cost, 71.61% on time and 15.33% quality. Prior to the dynamic simulation, the planned budget for the project was £545 million and was expected to be completed in 3 year. Later, the planned budget of the project was revised to £776 million and that of the planned completion time to 6 years. After simulation was performed, the result was validated against the real system to reveal the actual STEEP risks implication on the project performance. The validation results revealed that the actual project cost was overrun by £270.266 million while the project completion time also was exceeded by a 2.148 years as compared to the original project cost and time variations of £231 million and 3 years respectively. These results also indicated the accuracies of this simulation on cost and time were 83% and 72% respectively for the two significant overruns.

Quality of project management. The simulation results further revealed that the quality of project management was impacted by 15.33% (see Table 2). However, there was no available historical data on the original level of project's quality deficiency to be validated against with this output. With regard to the high accuracy on OBS described above, it is expected that further research into project management performance at the ETN project could make an interpretation possible to justify this simulation result with reliable evidence to be collected from literatures of the project, and this is based on an assumption that there is an inherent connection between OBS and quality of project management.

The hypothesized system, which was initially made up by expert's knowledge according to the Sdanp framework, has hence been examined through a comparison between the real project system and computer simulation in this experiment, and there are interesting results from the experiment to inform further practice on megaproject management in terms of early warnings with quantitative indicators on important issues such as the impact of STEEP risks, OBS, and the quality in project delivery.

Table 2: Experimental data validity on the ETN project

Original project information					
Cost (£ million)	Planned Project Budget (PPB)			545	
	Revised Project Budget			776	
	Project Cost Variation			231	
Duration (year)	Original Planned Duration (OPD), 2011			3	
	Expected New Duration, 2014			6	
	Completion Duration Variation			3	
Risks	Simulated project information (SPI)			Validated project information	
	Level of risk impact on project performance (%)				
	SPI on Cost (SPI_C)	SPI on Time (SPI_T)	SPI on Quality (SPI_Q)	Cost (£ million) ($Cost = SPI_C * PPB$)	Duration (year) ($Time = SPI_T * OPD$)
Social risks	12.00	6.00	1.00	65.400	0.180
Technical risks	1.24	0.43	0.15	6.758	0.013
Economic risks	22.36	30.74	8.88	121.862	0.922
Environmental risks	11.43	29.30	3.35	62.294	0.879
Political risks	2.56	5.14	1.95	13.952	0.154
Total impact	49.59	71.61	15.33	270.266	2.148

5. Conclusions

Sdanp framework. The goal of using Sdanp method for risk analysis, instead of eliminating all risks from the project, is to identify and recognize the significant risk challenges and to describe possible consequences of those challenges throughout their complex interactions on project performance over time so that an appropriate management response can be initiated to mitigate those challenges. From this point of view, it is more appropriate to assess project risks at construction planning stage by using the Sdanp method in order to develop a well risk-informed construction plan, and this process can also be improved through the use of building information models (BIMs) to connect extensively with design, construction and operation. Further research is therefore necessary to focus on BIM integrated Sdanp method.

Experiment. The Sdanp method described in this article is to gain a fuller understanding on interrelationships across multiple risk variables and their impact through interactions in megaproject delivery system at construction stage. The experimental case study on the ETN project was conducted to demonstrate the effectiveness and potential value of this new RAM. It is recommended that Sdanp could be applied in more megaproject cases to further add value to risk management practice alongside its managerial processes, in particular to risk identification, risk quantification, risk management planning, and risk control.

Findings. It has been found from the experimental case study that the feedback and endogenous perspective of Sdanp method for risk assessment and simulation is very powerful, widening the range for devising effective management solutions. It is an appropriate approach to holistically managing and modelling megaproject risk dynamics to which the traditionally used RAMs (BSI, 2010) may be less efficiency in terms of the differences from the unique integral use of four RAMs through Sdanp, which can empower the use of not only accumulated computable knowledge, collected from an expert group, about STEEP risks, but also networked measurements reflecting interactions among all identified risks. The new method provides a strong potential and numerous distinctive benefits to the overall management process when risks and responses are under thorough consideration in megaproject delivery.

Contributions. This article tries to introduce Sdanp as a new risk analysis methodology to facilitate an integral use of four RAMs, including ANP, ERA, RI, and SD, although its name was given by combining SD and ANP only. The research being described in this article has demonstrated how Sdanp could work for the ETN project. With regard to developing the theory of risk analysis, the Sdanp is a successful attempt to form a process that combines the four RAMs. For a contribution to the practice, this article and its described research have shown probably the first experiment in the world to explore an analytical solution that can predicate OBS in megaproject delivery. It is expected that this article could well inform academics and professionals with regard to its usefulness and potential in megaproject practice as well as further research.

Limitations. The research described here was the first attempt that the authors have made to explore for a useful solution to tackle major challenges such as the OBS in megaproject delivery. The choice of the integral use of four RAMs, including ANP, ERA, RI, and SD, was made based on the authors' experiences gained from using these methods individually in their previous megaproject oriented research. For the research described in this article, the authors want to detect the effectiveness of an integral use of these RAMs to tackle overrun problems in megaproject delivery. While interest has been attracted from professionals at top companies such as AECOM on megaprojects such as the Crossrail project in London after the experiment conducted for the ETN project was finished in Edinburgh, there is no other experiment to be described here in terms of the robustness of the Sdanp method. This is a limitation of this article, and further research is anticipated to include more experimental case studies to justify the robustness of Sdanp method for generic and/or bespoke applications.

Further research and development. It has been also noticed in the development of Sdanp framework that it has potential to add some other technical routes by incorporating additional RAMs given in BS EN 31010:2010 Risk management: Risk assessment techniques (BSI, 2010), as well as risk management activities through an integration (Levine, 1993) of a dependable Risk Breakdown Structure (RBS) (see Table 3 in Annex as an example) connecting with the Organization Breakdown Structure (OBS) and the Work Breakdown Structure (WBS) to form well informed and precise planning and control within a project information model such as Building Information Model (BIM) in megaproject risk management. As a tested method, it can be further applied in other megaprojects to provide added value to risk management processes, in particular to risk identification, qualitative and quantitative risk analysis, risk management planning, risk response planning, as well as risk monitoring and control.

Remarks. In response to the persistent problem of OBS in megaproject delivery, this article describes an experiment, which is probably the first one of its kind in the world to quantify such overruns in a technical way that can be used to effectively tackle the problem by providing predictive information through simulation for decision-making support. The experiment described in this article has achieved predictive accuracies that are not only promising but also encouraging for further research into improved models for a higher predictive accuracy. Due to the sensitivity and availability of data and information from the case project, this manuscript has a collection of suitable data and information to clarify the process of the proposed methodology, which is expected to inform both research and practice with such an promising experiment with its potential in relation to megaproject delivery, and the authors are keen to collaborate with academics and professionals to expand the usage of Sdanp in the future. In the process of preparing this manuscript, there was a collaboration with AECOM for using Sdanp in the Crossrail project, and it is not the purpose for this manuscript to describe another case study here.

6. Recommendations

The Sdanp method provides a new approach to risk analysis at the planning stage of megaproject delivery, it can be very useful for project planning and control at both strategic and tactic level to tackle risks more effectively and efficiently with regard to the principles of risk management (ISO, 2018), which requires a work procedure that is integrated, structured and comprehensive, customized, inclusive, and dynamic to use the best available information with considerations on human and cultural factors through continual improvement. It is a timely attempt to explore dependable technical solutions that can effectively deal with consistent problems such as OBS in megaproject delivery, and the authors would like to recommend Sdanp method for both academic research and professional practice in relation to risks oriented megaproject management, which has been identified critical to the performance of megaproject delivery in terms of OBS (Flyvbjerg, et al., 2003; Flyvbjerg, 2017), so as to eliminate the possibility and degree of chaos (Swanson, 2012) in megaproject delivery.

The procedure to implement Sdanp framework for megaproject risk management needs measures to control the risk posed by the interrelationship and interactions of STEEP risk variabilities, which may lead to poor project performance. It is important to further understand the combined impacts of various disturbances caused by interconnected STEEP risks so as to more effectively manage such risks in the delivery of individual megaprojects, and further research with the use of Sdanp method in more case projects is therefore necessary.

From the practice of megaproject delivery point of view, according to promising results from the reported experimental case study in this article, the authors would like to recommend the Sdanp method as a useful tool for clients and main contractors to improve the effectiveness, efficiency as well as dependence of risk management, and consequently the performance of megaproject management in relation to cost, time, and quality, etc. The integration of Sdanp process with an ordinary risk management procedure can benefit megaproject management in several ways, including

- Holistic risk identification,
- Enhanced risk management planning,
- Comprehensive (qualitative and quantitative) risk analysis,
- Informed risk response planning, and
- Continuous risk monitoring and control.

A brief description about these benefits are given below.

Holistic risk identification. The Sdanp method can support risk identification at project planning stage, which is crucial phase of megaproject risk management (Sanchez-Cazorla, et al., 2016), and it can be conducted in a qualitative way through using causal loop diagrams in addition to the qualitative way to define risk set. Among all specific STEEP risks (See Annex as an example), which were customized for individual megaproject, it is possible to identify which feedback loops favour or counter the occurrences of such risks so that the direct or indirect impacts of the project magnitude can be understood at an earlier stage.

Enhanced risk management planning. For risk management planning under a thorough consideration about STEEP issues and their possible interactions in megaproject delivery, feedback loops concerning project risks can further be used by planners to pro-actively test through forecasting and diagnosing the likely outcomes of the current project plan. Results from Sdanp simulation can then be used to improve project plan upon risk management.

Comprehensive risk analysis. The Sdanp method makes it possible to use causal loop diagrams to analyse all prioritised project 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 be used to identify and capture the full impacts of potential 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 risks occurrences and impacts on megaprojects during construction.

Informed risk response planning. The Sdanp method can be effectively used to support risk response planning in megaproject delivery in three ways, including

- Provide a feedback perspective for risk 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 a powerful tool to support project managers to devise effective responses.

Continuous risk monitoring and control. The Sdanp method is an effective tool for risk monitoring and control. Through the cause and effects diagrams, early signs of unperceived risk emergence can be identified to avoid aggravation. In addition, simulated models can provide an effective monitoring and control mechanism for continuous risk diagnosis throughout the period of megaproject delivery.

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Annex I: Knowledge gap

A recent literature review (Chen, 2019) identified that one of the major challenges in megaproject delivery is the consistent OBS across numerous cases, in addition to some other challenges such as professional competence and project sustainability. While there have been many case studies, project reviews, and statistics about megaproject development, the problem of overruns is still a big challenge in connection with the project delivery, and it is therefore expected that new technical solutions can be developed and introduced to assist the megaproject management team to effectively tackle this problem. The knowledge gap that the authors want to bridge through the research being described is the lack of technical solution that can prioritise risks and predict the consequences of identified risks within a dynamic project environment.

A further literature review, which focuses on the current status of using quantitative risk analysis methods such as those given in the British Standard *BS EN 31010:2010 Risk management: Risk assessment techniques* (BSI, 2010), was conducted by using the three generic search terms listed below in turn through the Google search engine online:

- Search Term 1: "Risk analysis method RAM_i " ($i=01, 02, \dots, 32$) AND "Risk assessment" AND Megaproject
- Search Term 2: "Risk analysis method RAM_i " ($i=01, 02, \dots, 33$) AND "Risk analysis method RAM_j " ($j=01, 02, \dots, 33$) AND "Risk assessment" AND Megaproject
- Search Term 3: "Risk analysis method RAM_i " ($i=01, 02, \dots, 33$) AND "Risk analysis method RAM_j " ($j=01, 02, \dots, 33$) AND "Risk analysis method RAM_k " ($k=01, 02, \dots, 33$) AND "Risk assessment" AND Megaproject. Note: more than three RAMs can be added until the search gives a satisfactory result.

Tables A1 and A2 summarise data collected from the search, and provide a profile about the current status of using recommended risk assessment methods (BSI, 2010) in the context of megaproject delivery. The results from this survey were used to interpret the knowledge gap for which this research was dedicating to fill.

It has emerged from the search results summarised in Table A1 that there is currently a various amount of usages across the 32 RAMs recommended by BSI (2010). According search results presented in Table A1, which was a collection of findings from using Search Term 1, it looks individual tools and techniques listed in the British Standard (BSI, 2010) have been applied in either research or practice in megaproject risk assessment across many cases, and the amount of such applications varies from the nature of individual methods themselves. According to findings from the search, it was noticed that the method RAM31 Multi-criteria decision analysis (MCDA) was ranked 8th among the 32 methods in Table A1, and this is an indication that the MCDA method is one of the most useful methods for risk assessment in megaproject delivery.

A further search through the use of Search Term 2 and 3 was then conducted to identify what this research can do with regard to filling a knowledge gap in megaproject risk assessment. Results from this search are given in Table A2 in relation to the use of two search terms respectively. Details about how the two search terms were used in the process to further identify knowledge gap are given below.

Six methodological methods were chosen in the process mentioned above, and these methods are listed in Table A2 under the use of Search Term 1. The reason to use this search term after Table A1 is that it was an purpose for this research to give a further look into the used of specific MCDA methods, which include analytic hierarchy process (AHP) and analytic network process (ANP), and the other three methods, including environmental risk assessment (ERA), risk index (RI), and system dynamics (SD), which are of the authors' interest with regard to the goal of this research.

While MCDA is recommended by BSI (2010), there was not specific tools and techniques for MCDA. AHP and ANP were then chosen to detect how wide this two popular MCDA methods have been used in risk assessment for megaproject delivery. In addition, it was an intension to establish an understanding through a comparison between the two methods in terms of their related applications, and this comparison was helpful in the process to detect the knowledge gap. As shown in Table A2, although ANP is a relevantly new method than AHP, it has a sound higher record (Refer to the ranking in Table A1) of usages in risk assessment for megaproject. Because ANP is a generic form of AHP but has methodological advantages in terms of the need for inclusive decision making among interconnected influence factors, which are risk

factors in relation to what this research focuses on, a further check on the use of ANP in this research was made through the use of Search Term 2 and 3 respectively.

Although BSI (2010) has recommended 32 RAMs for risk assessment, some other methods such as the SD as a specific RAM was not included. Because the usefulness of SD in risk assessment, it was then included in the further search in this process too. In comparison with findings given in Table A1, the popularity of SD in risk assessment is compatible with Delphi analysis, and this is an indication that the acceptance of SD needs to be considered for possible inclusion in this research upon an identified knowledge gap.

Table A1: The adoption of risk assessment methods for megaproject delivery

Code	Tools and techniques for risk assessment (BSI, 2010)		Search results from Google via Internet Explorer 11 (As of 01/06/2019)
	Name of the method	Ranking upon usage	
	Look-up methods		
RAM01	Check list	11	2,900
RAM02	Primary hazard analysis	30	9
	Supporting methods		
RAM03	Brainstorming	7	5,720
RAM04	Delphi analysis	1	88,500
RAM05	Human reliability analysis	23	243
RAM06	Structured interview	13	1,800
RAM07	SWIFT analysis	5	8,970
	Scenario analysis		
RAM08	Business impact analysis	16	482
RAM09	Cause and consequence analysis	32	3
RAM10	Cause and effect analysis	20	319
RAM11	Event tree analysis	18	375
RAM12	Fault tree analysis	12	2,110
RAM13	Root cause analysis	6	8,720
RAM14	Scenario analysis	9	3,350
RAM15	Toxicological risk assessment	21	308
	Function analysis		
RAM16	Failure mode and effect analysis	17	442
RAM17	Hazard analysis & critical control points	24	176
RAM18	Hazard and operability studies	27	96
RAM19	Reliability centred maintenance	22	276
RAM20	Sneak circuit analysis	31	4
	Controls assessment		
RAM21	Bow tie analysis	26	123
RAM22	Layer of protection analysis	25	127
	Statistical methods		
RAM23	Bayesian analysis	15	1,230
RAM24	Markov analysis	28	71
RAM25	Monte Carlo simulation	3	26,500
	Other methods		
RAM26	Consequence/Probability matrix	(29)/19	24/332
RAM27	Cost/benefit analysis	2	32,700
RAM28	Decision tree	10	3,020
RAM29	Environmental risk assessment	4	11,900
RAM30	FN curve	29	20
RAM31	Multi-criteria decision analysis	8	4,040
RAM32	Risk index	14	1,600

In response to the persistence of major problems such as OBS, the assumption made for risk assessment is to integrally use two or more powerful RAMs in order to improve the performance of risk assessment and control. Search Term 2 was therefore put forward with the aim to detect the status of an integral use of two specific RAMs for megaproject. Under this purpose, three RAMs including ANP, ERA, and SD were chosen for paired integration. This choice was made according to findings under Search Term 1 about their individual usages, as well as the authors' previous experiences in using these three methods in megaproject oriented research, including

- The use of ANP for one urban regeneration project (Chen and Khumpaisal, 2009),
- The integral use of ANP and ERA for three international hub airports (Chen *et al.*, 2011), and
- The use of SD for one dam project (Mahato and Ogunlana, 2011).

Table A2: A verification of an integrated risk assessment method for megaproject delivery

Tools and techniques for risk assessment		Search results from Google via Internet Explorer 11 (As of 02/06/2019)
Code	Name of the method	
<i>Search Term 1</i>		
RAM29	Environmental risk assessment (ERA)	11,100
RAM31	Multi-criteria decision analysis	2,590
RAM31.1	Analytic hierarchy process (AHP)	5,380
RAM31.2	Analytic network process (ANP)	1,540
RAM32	Risk index (RI)	1,620
RAM33	System dynamics (SD)	86,100
<i>Search Term 2</i>		
	ERA + ANP	257
	ERA + SD	791
	ANP + SD	480
<i>Search Term 3</i>		
	ERA + ANP + SD	171
	ERA + ANP + RI + SD	5

It is obvious, as shown in Table A2, that the amount of results from using Search Term 2 has dropped significantly in comparison with what has been found under Search Term 1. It was eventually found that there were only five results under Search Term 3 with regard to the integral use of four identified RAMs, including ANP, ERA, RI, and SD; and among those five results, which were websites of collections of publications, there was no methodology proposed for risk assessment through an integral use of these four RAMs. Therefore, it was concluded in the literature review that this research needs to focus on the identified knowledge gap where there was a lack of research into a new methodology, which integrates the use of these four RAMs for risk assessment in megaproject delivery.

Annex II: Risk factors selected for analysis in case study

A set of generic risk factors were selected through extensive literature review for risk assessment and simulation within Sdanp framework for the experimental case study. Factor selection was conducted based on the authors' knowledge and judgments among findings from the use of the following search terms on professional databases at ASCE, ICE, and the Web of Science respectively, in addition to Google:

- "Social risk" AND megaproject
- "Technical risk" AND megaproject
- "Economic risk" AND megaproject
- "Environmental risk" AND megaproject
- "Political risk" AND megaproject

For the experimental case study, the ETN project was used as the keyword of the second part of each search term listed above to replace megaproject, and there is a number of evidence listed below that highlight the significance of identified risk factors on this case project:

- Social risks
 - Social grievances (BBC News, 29/04/2008 and 07/12/2009; The Scotsman, 22/12/2009; McIntosh, 2009)
 - Multi-level decision making bodies (Transport Initiatives Edinburgh, 2007)
 - Disputes (Aitken, 2009; Henderson, 2010a; Dalton, 2010)
 - Legal Actions (Gilbert, 2008; Henderson, 2010a)
 - Stakeholder's criticism/pressure (BBC News, 07/12/2009; Marshall, 2010)
 - Social Issues (BBC News, 29/04/2008 and 07/12/2009; The Scotsman, 22/12/2009; McIntosh, 2009)
- Technical risks
 - Project scope changes (Ferguson, 2010; BBC News, 17/09/2011)
 - Ground conditions on given project sites (Severin, 2011)
 - Inadequate project complexity analysis (BBC News, 17/09/2011)
 - Modification to project specification (The Scotsman, 31/05/2013)
 - Technical difficulties in utilities diversions (Audit Scotland, 2007)
 - Engineering and design change (BBC News, 17/09/2011)
 - Project quality deficiency (BBC News, 17/09/2011; The Scotsman, 09/03/2011, 31/05/2013 and 09/08/2013)
 - Supply chain breakdown (Mumford, 2011)
 - Rework (The Scotsman, 31/05/2013 and 09/08/2013)
 - Project time overruns (Henderson, 2009 and 2010b; Lowe, 2010; Marshall, 2010; STV News, 10/03/2010; Wright, 2010)
 - Project cost overruns (Ferguson, 2010; Wright, 2010; Severin, 2011; Marshall, 2011; BBC News, 19/08/2011)
- Economic risks
 - Incorrect project cost estimate (Ferguson, 2010; Wright, 2010; Leask, 2010; Severin, 2011; Marshall, 2011; BBC News, 19/08/2011)
 - Incorrect project time estimate (Gilbert, 2008; Henderson, 2010a; STV News, 10/03/2010)
 - Wage inflation (Wright, 2010; BBC News, 20/06/2012)
 - Global economic recession (Johnson, 2008; BBC News, 2009)
 - Cost and delays due to utilities diversions (Henderson, 2009; Marshall, 2010; Wright, 2010)
 - Changes in inflation as construction works proceed (The Scotsman, 23/06/2010; BBC News, 02/09/2011)
 - Funding problems (Audit Scotland, 2007; Severin, 2011; BBC News, 30/08/2011)
- Environmental risks
 - Freezing temperatures (The Scotsman, 09/01/2010; Mumford, 2011)
 - Pollution (water, air, and noise etc.) (BBC News, 13/12/2011; Chen et al., 2011)
- Political risks
 - Lack of political support (opposition) (Audit Scotland, 2007; BBC News, 30/08/2011)
 - Lack of partner support (Audit Scotland, 2007; BBC News, 30/08/2011)
 - Political indecision (BBC News, 30/08/2011)
 - Project termination (Lowe, 2010)
 - Contractual disputes (Aitken, 2009; Henderson, 2010a; Dalton, 2010)

Table 3 was used to collect experts' judgments regarding the importance of risk clusters and risk factors, and the collected data were then used in the ANP model for risk prioritisation. Regarding how to use the data collection table for ANP, please refer to details described by Chen (2010) for a cybernetic model, which was used in this research as an efficient Pair-Wiser approach to facilitate data collection and pairwise process for ANP. The efficiency of this approach was further verified in this research.

Data collected through the use of Table 3 were processed in two ways in the experimental case study. The first usage of collected data was to do pairwise comparisons for the ANP model, and second usage of collected data was to detect the weight of each main criterion and sub-criterion. This collection has helped to establish an in-depth understanding about STEEP risks in the ETN project.

Table 3: Data collection for risk prioritisation through ANP

Risk clusters	Cluster score	Risk factors	Element score
1. Social risks		1.1 Disputes	
		1.2 Legal actions	
		1.3 Multi-level decision-making	
		1.4 Social grievances	
		1.5 Social issues	
		1.6 Stakeholder's criticism/ pressure	
		1.7 Treats to person and asset security	
2. Technical risks		2.1 Engineering and design amendments	
		2.2 Failure to meet specified standards	
		2.3 Dynamic ground conditions	
		2.4 Inadequate project analysis	
		2.5 Inadequate site investigation	
		2.6 Overruns caused by inaccurate project cost estimate	
		2.7 Overruns caused by inaccurate project time estimate	
		2.8 Project deficiency on activities and performance	
		2.9 Project scope changes	
		2.10 Supply chain breakdown	
		2.11 Technical difficulties in utilities diversions	
		2.12 Unforeseen modification to project specification	
3. Economic risks		3.1 Changes on government funding policy	
		3.2 Changes on inflation during construction	
		3.3 Changes on material prices	
		3.4 Changes on energy prices	
		3.5 Changes on currency exchange rates	
		3.6 Changes on taxation	
		3.7 Economic recession	
		3.8 Expenditures upon accidents/incidents & disturbances	
		3.9 Expenditures upon technical difficulties	
		3.10 Problems with public and/or private funding	
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Figure 1: Sdanp framework for risk assessment and simulation

Figure 2: ANP model for risk prioritization

Legend:

., —————> A causal relationship

+ (-) signs at the arrowheads indicate that the effect is positively (negatively) related to the cause.

R denotes reinforcing (positive) loop and B, the balancing (negative) loop

// sign on the arrow indicates material and/or information delay

Figure 4: Three components of SD models

Figure 5: A simple stock and flow model for social risks

Figure 6: Measured impacts of STEEP risks

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Table A1: The adoption of risk assessment methods for megaproject delivery

Code	Tools and techniques for risk assessment (BSI, 2010)		Search results from Google via Internet Explorer 11 (As of 01/06/2019)
	Name of the method	Ranking upon usage	
	<i>Look-up methods</i>		
RAM01	Check list	11	2,900
RAM02	Primary hazard analysis	30	9
	<i>Supporting methods</i>		
RAM03	Brainstorming	7	5,720
RAM04	Delphi analysis	1	88,500
RAM05	Human reliability analysis	23	243
RAM06	Structured interview	13	1,800
RAM07	SWIFT analysis	5	8,970
	<i>Scenario analysis</i>		
RAM08	Business impact analysis	16	482
RAM09	Cause and consequence analysis	32	3
RAM10	Cause and effect analysis	20	319
RAM11	Event tree analysis	18	375
RAM12	Fault tree analysis	12	2,110
RAM13	Root cause analysis	6	8,720
RAM14	Scenario analysis	9	3,350
RAM15	Toxicological risk assessment	21	308
	<i>Function analysis</i>		
RAM16	Failure mode and effect analysis	17	442
RAM17	Hazard analysis & critical control points	24	176
RAM18	Hazard and operability studies	27	96
RAM19	Reliability centred maintenance	22	276
RAM20	Sneak circuit analysis	31	4
	<i>Controls assessment</i>		
RAM21	Bow tie analysis	26	123
RAM22	Layer of protection analysis	25	127
	<i>Statistical methods</i>		
RAM23	Bayesian analysis	15	1,230
RAM24	Markov analysis	28	71
RAM25	Monte Carlo simulation	3	26,500
	<i>Other methods</i>		
RAM26	Consequence/Probability matrix	(29)/19	24/332
RAM27	Cost/benefit analysis	2	32,700
RAM28	Decision tree	10	3,020
RAM29	Environmental risk assessment	4	11,900
RAM30	FN curve	29	20
RAM31	Multi-criteria decision analysis	8	4,040
RAM32	Risk index	14	1,600

Table A2: A verification of an integrated risk assessment method for megaproject delivery

Tools and techniques for risk assessment		Search results from Google via Internet Explorer 11 (As of 02/06/2019)
Code	Name of the method	
<i>Search Term 1</i>		
RAM29	Environmental risk assessment (ERA)	11,100
RAM31	Multi-criteria decision analysis	2,590
RAM31.1	Analytic hierarchy process (AHP)	5,380
RAM31.2	Analytic network process (ANP)	1,540
RAM32	Risk index (RI)	1,620
RAM33	System dynamics (SD)	86,100
<i>Search Term 2</i>		
	ERA + ANP	257
	ERA + SD	791
	ANP + SD	480
<i>Search Term 3</i>		
	ERA + ANP + SD	171
	ERA + ANP + RI + SD	5

Table 1: Summary of outputs from Sdanp analysis

Risks		RPI	Estimated level of risk (%)					
<i>Cluster</i>	<i>Code</i>	(%)	<i>Min</i>	<i>Max</i>	<i>Mean</i>	<i>Median</i>	<i>SD</i>	<i>Norm</i>
Social risks	P_{R1}	0.13	-31.00	48.00	19.00	20.00	18.00	96.00
Technical risks	P_{R2}	0.30	30.00	55.69	40.48	39.28	7.41	18.31
Economic risks	P_{R3}	0.25	1.72	33.00	21.51	26.07	10.73	49.86
Environmental risks	P_{R4}	0.16	6.59	18.78	14.86	14.86	16.39	3.85
Political risks	P_{R5}	0.17	17.00	42.10	35.20	37.70	7.04	20.00

Table 2: Experimental data validity on the ETN project

Original project information					
Cost (£ million)	Planned Project Budget (PPB)		545		
	Revised Project Budget		776		
	Project Cost Variation		231		
Duration (year)	Original Planned Duration (OPD), 2011		3		
	Expected New Duration, 2014		6		
	Completion Duration Variation		3		
Risks	Simulated project information (SPI)			Validated project information	
	<i>Level of risk impact on project performance (%)</i>				
	SPI on Cost (SPI_C)	SPI on Time (SPI_T)	SPI on Quality (SPI_Q)	Cost (£ million) ($Cost = SPI_C * PPB$)	Duration (year) ($Time = SPI_T * OPD$)
Social risks	12.00	6.00	1.00	65.400	0.180
Technical risks	1.24	0.43	0.15	6.758	0.013
Economic risks	22.36	30.74	8.88	121.862	0.922
Environmental risks	11.43	29.30	3.35	62.294	0.879
Political risks	2.56	5.14	1.95	13.952	0.154
Total impact	49.59	71.61	15.33	270.266	2.148

Table 3: Data collection for risk prioritisation through ANP

Risk clusters	Cluster score	Risk factors	Element score
1. Social risks		1.1 Disputes	
		1.2 Legal actions	
		1.3 Multi-level decision-making	
		1.4 Social grievances	
		1.5 Social issues	
		1.6 Stakeholder's criticism/ pressure	
		1.7 Treats to person and asset security	
2. Technical risks		2.1 Engineering and design amendments	
		2.2 Failure to meet specified standards	
		2.3 Dynamic ground conditions	
		2.4 Inadequate project analysis	
		2.5 Inadequate site investigation	
		2.6 Overruns caused by inaccurate project cost estimate	
		2.7 Overruns caused by inaccurate project time estimate	
		2.8 Project deficiency on activities and performance	
		2.9 Project scope changes	
		2.10 Supply chain breakdown	
		2.11 Technical difficulties in utilities diversions	
		2.12 Unforeseen modification to project specification	
3. Economic risks		3.1 Changes on government funding policy	
		3.2 Changes on inflation during construction	
		3.3 Changes on material prices	
		3.4 Changes on energy prices	
		3.5 Changes on currency exchange rates	
		3.6 Changes on taxation	
		3.7 Economic recession	
		3.8 Expenditures upon accidents/incidents & disturbances	
		3.9 Expenditures upon technical difficulties	
		3.10 Problems with public and/or private funding	
		3.11 Project time delays of all forms	
		3.12 Wage inflation	
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